Detecting spatial variation in hydrology and carbon export across a lake-rich permafrost landscape, Old Crow Flats, Yukon, Canada

Daniel Hughes, BSc. (Honours)

Department of Earth Sciences

Submitted in partial fulfillment of
the requirements for the degree of

Masters of Science

Faculty of Mathematics and Science, Brock University
St. Catharines, Ontario

**Abstract**

Lake-rich permafrost landscapes are widespread across northern regions and provide refuge for abundant wildlife and resources for local communities. Evidence suggests that these landscapes are highly sensitive to changes in climate. The traditional territory of the Vuntut Gwitchin First Nation, Old Crow Flats (OCF), YK, is a vast 5600-$km^2$ lake-rich landscape that is internationally recognized for its ecological and cultural integrity. Pronounced changes in lake and river water levels and land cover compositions have been observed during recent decades by local community members and in scientific studies. Research presented here focuses on enhancing our understanding of spatial patterns in hydrology and carbon export across OCF, using a suite of water chemistry parameters, carbon concentrations and water and carbon isotope tracers. The spatial patterns detected are providing an important reference for ongoing investigations of how changing climate and lake-rich landscapes are influencing water and carbon balances.

Keywords: permafrost; water isotope tracers; water chemistry; spatial analysis; carbon concentrations

**Acknowledgments**

There are a number of people I would like to acknowledge for their help throughout my Master's degree but I will begin with my supervisor, Dr. Kevin Turner. Thank you for your guidance, time, support, and knowledge, you have provided throughout these past two years. I could not have done this without your help, and I will be forever grateful for the opportunity. I am also appreciative for the insight and support of Dr. Michael Pisaric and Dr. Francine McCarthy, your suggestions have only improved my final work. Thank you to the agencies which made my graduate work possible, Natural Sciences and Engineering Research Council, Polar Continental Shelf Program, Northern Scientific Training Program, Ontario Graduate Scholarship, and Brock University.

I would like to acknowledge the Vuntut Gwitchin First Nation and residents of Old Crow, Yukon who provided a lot of help in the field, welcomed me to your Caribou Days celebration, and community dinner. Notably, I would like to thank Danny Kassi, Steven Frost, Eleanor Charlton, Dougie Charlie, Erika Tizya, Georgie Moses, Mary-Jane Moses, and Megan Williams. Your knowledge and support in Old Crow, and out on Old Crow Flats was an immense help.

Thank you to Parks Canada for your support and help in the field over the past 2 years. I would specifically like to thank Jeffrey Peter and Amanda Frost for taking me on your annual boat trip up the Old Crow River and accommodating my sampling throughout.

To my colleagues, friends, and founding students of the Water and Environment Lab (WEL) at Brock; Cait Garner, Rebecca Gunter, Tyler Prince, Zach Harmer, Brent Thorne, Dana Harris, Emily Ham. Thank you for your support, listening to every thesis presentation multiple times over the course of 2 years, and providing insightful questions and suggestions to improve my work.

A special thanks to Tyler Prince for your help in Old Crow collecting and filter water samples. Finishing at a reasonable hour at night was an awesome improvement over the previous season, and the company in the lab was also much appreciated. Thanks also to Zach Harmer for the hours spent on timmies breaks and wandering Mackenzie Chown discussing Rstudio and Statistics. They will be missed.

To my friends, who on Thursday nights would take my mind off thesis work, watch some football and have lots of laughs along the way, I will always be in your debt. To my family, your never-ending support and encouragement continued to pushed me, especially on the days I really needed it.

Finally, to Trudi, who has had to listen to me talk about this project for what probably feels like forever. I could not have done this without you and look forward to our next adventure together.

To those I may have missed, thank you!

**Table of Contents**

**List of Figures**

**List of Tables**

## List of Abbreviations

| | |
|---|---|
| BASL | Biogeochemical Analytical Service Laboratory |
| BF | Black Fox Creek |
| Ca | Calcium |
| Chl *a* | Chlorophyll *a* |
| Cl | Chlorine |
| d-excess | Deuterium excess |
| DIC | Dissolved Inorganic Carbon |
| DOC | Dissolved Organic Carbon |
| GMWL | Global Meteoric Water Line |
| HDPE | High-Density Polyethylene Environmental Sample Bottles |
| HPLC | High-performance liquid chromatography |
| JC | Johnson Creek |
| K | Potassium |
| KC | King Edward Creek |
| LEL | Local Evaporation Line |
| LIS | Laurentide Ice Sheet |
| Mg | Magnesium |
| Na | Sodium |
| $NO_2 + NO_3$ | Nitrite and Nitrate |
| OCF | Old Crow Flats |
| OCR | Old Crow River |
| PARTNERS | Pan-Arctic Transport of Nutrients, Organic Matter and Suspended Sediments |
| PC | Potato Creek |
| PCA | Principal Component Analysis |
| PR | Porcupine River |
| RDA | Redundancy Analysis |
| RTS | Retrogressive thaw slump |

| | |
|---|---|
| SC | Schaeffer Creek |
| $SiO_2$ | Silicon dioxide |
| SLAP | Standard Light Antarctic Precipitation |
| $SO_4$ | Sulfate |
| TC | Thomas Creek |
| Tim C | Timber Creek |
| TSS | Total Suspended Solids |
| Turb | Turbidity |
| UAV | Unmanned aerial vehicle |
| VGFN | Vuntut Gwitchin First Nation |
| VPDB | Vienna Pee Dee Belemnite |
| %VSMOW | Vienna Standard Mean Ocean Water |
| yr BP | Year before present |
| $\delta\ ^{13}C$ DIC | $Carbon^{13}/Carbon^{12}$ DIC ratio |
| $\delta\ ^{13}C$ DOC | $Carbon^{13}/Carbon^{12}$ DOC ratio |
| $\delta^{18}O$ | $Oxygen^{18}/Oxygen^{16}$ ratio |
| $\delta^{2}H$ | $Hydrogen^{2}/Hydrogen^{1}$ ratio |

## List of Appendices

Chapter 1:

# General Introduction

## 1.1 Introduction

Lake-rich permafrost landscapes are abundant across northern regions (Brown et al., 1997, 2002) and provide valuable resources for northern communities. Research has shown that these landscapes have been highly sensitive to the changes in climate that have been pronounced across northern regions during recent decades. For example, temperatures have risen 0.6 degrees Celsius per decade over the last 30 years, twice the global average, which has lead to an increase in landscape change observed across the Arctic (IPCC, 2013). As well, there is likely going to be an increase in precipitation (Bintanja and Selten, 2014). Lake-rich landscape responses to changing climate have been variable with lake area remaining stable (Riordan et al., 2006), increasing (Smith et al., 2005; Jones et al., 2011), or decreasing (Labrecque et al., 2009; Jones et al., 2011) according to multiple geomorphic and climatic conditions. Other landscape changes observed in these areas include the occurrence of retrogressive thaw slumps (Kokelj and Jorgenson, 2013) and widespread proliferation of shrub vegetation (Myers-Smith et al., 2011). It is unclear how these landscape changes are impacting downstream hydrology and water quality. While these landscapes are naturally dynamic, evidence indicates that their response to climate has intensified during recent decades. Enhancing our knowledge of these landscapes using effective monitoring approaches is vital for anticipating how the hydrology, nutrient cycling, and ecology of these important systems will respond to future change and impact northern communities.

Formation and subsequent changes of thermokarst lakes can be generally characterized by lake expansion, drainage, permafrost recovery, and lake re-initiation. The formation process initially includes accumulation of surface water as permafrost subsides (Mackay, 1992) followed by coalescence of ponds and establishment of lake shorelines. Lakes can persist for thousands of years; however, they can undergo prolonged or rapid changes from expansion, drainage, or evaporation. Increasing surface area occurs as ice-rich shorelines subside (Mackay, 1997; Roy-Léveillée and Burn, 2010). Drainage will occur if lakes are adjacent to low-lying areas that they either expand into or connect via overflow channels (Wolfe and Turner, 2008) or along subsurface ice wedge cracks (Mackay, 1988). Lateral drainage can be significant with lakes loosing over 80% water volume within days to weeks (Turner et al., 2010), so these events have been identified as 'catastrophic'. Drainage can also occur internally when underlying taliks allow flow to connect vertically to groundwater (Yoshikawa and Hinzman, 2003). Once drained, permafrost recovery within the basin can occur within one year (Mackay, 1997), and shorelines begin to re-establish as the cycle re-initiates (Shur and Jorgenson, 2007). The frequency of lake drainage events has increased in many permafrost landscapes (Smith et al., 2005; Jones et al., 2011; Lantz and Turner, 2015), which suggests these systems have become more dynamic.

In addition to catastrophic lake drainage, many permafrost landscapes have experienced other biophysical changes including shrub proliferation (Myers-Smith et al., 2011, 2015), and erosional processes such as expansion of channel networks (Toniolo et al., 2009), river bank erosion (Costard et al., 2007), the occurrence of retrogressive thaw slumps (Lantz and Kokelj, 2008) and active layer detachment slides (Lamhonwah et al., 2017; Lafrenière et al., 2017). Recent studies have also found these changes are increasing in magnitude and spatial coverage (Kokelj et al., 2015; Myers-Smith et al., 2015). For instance, shrub vegetation has experienced widespread proliferation during recent decades (Myers-Smith et al., 2011, 2015) and accelerated erosion has initiated a greater number and larger retrogressive thaw slump events (Kokelj et al., 2015). Widespread increases in these events across the Arctic require continued research on future landscape change with continuing climate variability.

These landscape alterations can also affect downstream water chemistry, and sediment loading within these systems. The lateral drainage of thermokarst lakes can add water into other nearby lakes and river networks (Turner et al., 2014a). This addition of lake water could alter downriver hydrological conditions, changing water chemistry and isotope signatures. Erosional features such as retrogressive thaw slumps, which form due to the degradation of massive ice within the permafrost zone, can also have an impact on the hydrology. Retrogressive thaw slumps can lead to the exposure of organic top soils and mineral soils which have been previously frozen within the permafrost. Those soils are then available to erosional processes and runoff into the local hydrology, which can continue for decades (Kokelj et al., 2009; Kokelj and Jorgenson, 2013). Similar to retrogressive thaw slumps, active layer detachment slides expose organic and mineral rich soils which act as a flushing mechanism and mobilize solutes into the local hydrology (Lamhonwah et al., 2017; Lafrenière et al., 2017). Permafrost can also contain large concentrations of trapped organic carbon, and through these and other landscape changes, can become available for mineralization (Schuur et al., 2015). Increased influx of organic carbon can alter the local carbon budget, and lead to increased mineralization of $CO_2$ into the atmosphere (Schuur et al., 2015). Studying these landscape features and their effect on the hydrology is critical in our understanding of ecosystem dynamics and the permafrost-carbon feedback (Schuur et al., 2015). Also, monitoring changes in river hydrology could be used as an indicator of upstream landscape change.

Old Crow Flats (OCF), Yukon Territory, Canada is a lake-rich permafrost landscape that is the traditional territory of the Vuntut Gwitchin First Nation (VGFN) and is recognized as a Wetland of International Importance by the Ramsar Convention (1982). This landscape is a result of geomorphological and periglacial processes that occurred when the Laurentide Ice Sheet (LIS) bordered OCF to the east during the early Wisconsinan. At that time, the Old Crow River, which flowed into the Porcupine River, flowed east into and out the Mackenzie Delta. The LIS blocked the outflow from OCF and forced the formation of glacial lake Old Crow, flooding the OCF non-glaciated lowlands. The LIS retreated until the late Wisconsinan glacial advance and the lake re-formed, causing a catastrophic drainage through the western Upper Ramparts initializing the westward flow of the Porcupine (Zazula et al., 2004). The area drained leaving behind silt and clay rich sediments as well as prehistoric animal remains (Morlan, 2003). Today, the VGFN, who reside 25 km south of OCF in Old Crow, utilize resources from OCF to maintain traditional lifestyles. This 5600 $km^2$ landscape consists of over 8700 thermokarst lakes and ponds (Lantz and Turner, 2015) along with a dense river network incised into periglacial sediments of former glacial lake Old Crow (Morlan, 1980; Lauriol et al., 2002). The ~14,500 $km^2$ basin of OCF extends into the British, Richardson, Ogilvie and Old Crow mountain ranges and drains into the Yukon River Basin. OCF straddles the boreal-tundra transition zone and includes vegetation that can be generally classified as black spruce forest, shrub vegetation, tundra grasses and herbs and emergent hydrophilic plants in bogs and at lake edges. Members of the VGFN who have utilized resources from OCF for many generations have observed landscape changes during recent decades including shrub vegetation proliferation and lake drainages (Wolfe et al., 2011), which have been associated with warming climate conditions (Porter and Pisaric, 2011). They are concerned how climate-induced changes will influence future generations and their traditional lifestyle.

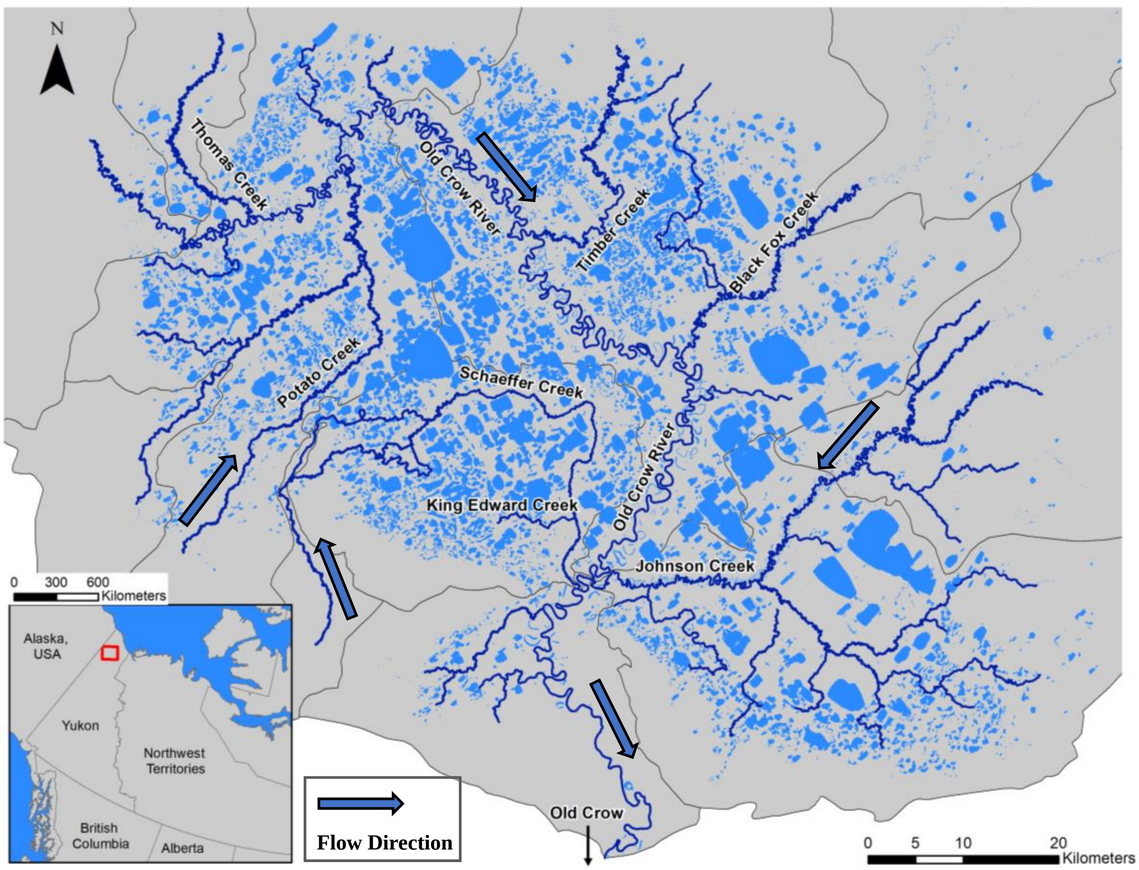



*Figure 1.1. Map of Old Crow Flats, Yukon Territory, Canada.*

Previous research in OCF has focussed on understanding spatial variability in lake hydrological and limnological conditions and the associated drivers (Turner et al., 2010; Tondu et al., 2013; Turner et al., 2014b; Balasubramaniam et al., 2015). Lake water balances across OCF are influenced by snowmelt, rainfall, and evaporation which are categorized based on catchment features (Turner et al., 2010, 2014b). These catchment features surrounding lakes such as tall shrubs and trees tend to capture windblown snow, increasing the influence of snowmelt, whereas tundra lakes tend to be rainfall dominated (Turner et al., 2014b). Variability in lake water balance also affects water chemistry, where greater snowmelt increases concentrations of nutrients and DOC, whereas greater rainfall inputs contain increased ion concentrations, conductivity and alkalinity (Balasubramaniam et al., 2015). Increases in nutrient and DOC concentrations have been linked to interactions between snowmelt and organic matter in vegetated catchments and increased ionic concentrations are mainly a factor of evaporation on lake water, as well as shoreline erosion and storm water runoff from mineral rich soils within tundra regions (Balasubramaniam et al., 2015). Studies have also highlighted the runoff generation processes in OCF (Turner et al., 2014a) where changes in source water as well as lake-to-river connections are identifiable through river isotope signatures. With an increasing number of lake draining events across OCF (Lantz and Turner, 2015), river water has been useful for detecting upstream landscape change (Turner et al., 2014a). Here we expand on previous work by identifying spatial variability in landscape influence on the river networks across OCF. The OCF drainage network is a conduit where we can capture insight of how upstream landscape change impact downstream environments.

## 1.2 Research Objectives

This work aims to build on previous studies by closely examining river water characteristics to evaluate the spatial variability of runoff generation processes in OCF, which is influenced by climate drivers. Key objectives include the following:

1. Characterizing lake-to-river connectivity across OCF using water isotope tracers;
2. Using a suite of water chemistry (nutrients, major ions, carbon concentrations) and isotope parameters ($\delta^{2}H$, $\delta^{18}O$, $\delta^{13}C$ DIC, $\delta^{13}C$ DOC) to identify spatial variation in the influence of lake water export on river hydrology including characterizing carbon export through DIC/DOC concentrations and $\delta^{13}C$ signatures;
3. Studying the influence of a permafrost disturbance (retrogressive thaw slump) on the Old Crow River carbon balance and water chemistry.

Identifying the spatial variability in lake and river hydrology and associations with changing landscape features will provide the basis to predict how hydrological features in OCF will respond to future climate change.

## 1.3 Research Methods

Water samples were collected from 22 rivers and 13 lake sites over the course of two days during three sampling campaigns conducted during July (24$^{th}$-25$^{th}$) 2015, May (26$^{th}$-27$^{th}$) and July (26$^{th}$-29$^{th}$) 2016 (Table 1.1). These samples were analyzed for water isotope compositions ($\delta^{2}H$, $\delta^{18}O$), carbon concentration and isotope compositions (DIC, DOC, $\delta^{13}C$ DIC, $\delta^{13}C$ DOC) and a suite of water chemistry parameters (nutrients, ions, carbon concentrations). Results were used to highlight spatial variability in hydrology and the influence of landscape features on downstream conditions.

*Table 1.1. Sample ID format for all lake and river sites collected over the three sampling periods (Figure 2.1) *JC3 taken from tributary mouth along Johnson Creek.*

| **Lake Sample ID** | **River Sample ID** | **River Name** | **Slump Samples** | **Sample Name** |
|---|---|---|---|---|
| OCF6 | OCR 1 – 7 | Old Crow River | SR / S1 runoff | Slump (Runoff) |
| OCF11 | BF 1 – 4 | Black Fox Creek | SD / S1 downriver | Slump (Downriver) |
| OCF19 | SC 1 – 4 | Schaeffer Creek | | |
| OCF26 | Tim C | Timber Creek | | |
| OCF29 | TC | Thomas Creek | | |
| OCF34 | KC | King Edward Creek | | |
| OCF35 | PC | Potato Creek | | |
| OCF37 | PR 1 – 2 | Porcupine River | | |
| OCF38 | JC 1 – 4* | Johnson Creek* | | |
| OCF46 | | | | |
| OCF48 | | | | |
| OCF49 | | | | |
| OCF55 | | | | |
| OCL1 | | | | |

## 1.4 Thesis Format

This thesis is organized into four chapters. Chapter 1 provides an introduction to the research conducted and background information on the study site (OCF). Chapter 2 will be the first article highlighting spatial variability in runoff generation processes across OCF. Chapter 3 will be the second and final article which will discuss spatial variability in carbon export across OCF. Chapter 4 summarizes key findings, highlighting their importance, the utility of the approaches used as well as discussing new questions and future work generated from these findings.

## 1.5 References


Balasubramaniam, A.M., Hall, R.I., Wolfe, B.B., Sweetman, J.N., Wang, X., Smith, R., 2015. Source water inputs and catchment characteristics regulate limnological conditions of shallow subarctic lakes (Old Crow Flats, Yukon, Canada). Can. J. Fish. Aquat. Sci. 72, 1058–1072. doi:10.1139/cjfas-2014-0340

Bintanja, R., Selten, F.M., 2014. Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. Nature 509, 479–482. doi:10.1038/nature13259

Brown, J., Ferrians, O., Heginbottom, J.A., Melnikov, E., 2002. Arctic map of permafrost and ground-ice conditions.

Brown, J., Sidlauskas, F.J., Delinski, G., 1997. Circum-Arctic map of permafrost and ground ice conditions.

Costard, F., Gautier, E., Brunstein, D., Hammadi, J., Fedorov, A., Yang, D., Dupeyrat, L., 2007. Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia. Geophys. Res. Lett. 34. doi:10.1029/2007GL030212

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC fifth assessment report. Cambridge Univ. Press, Cambridge, UK.

Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Walter Anthony, K.M., Romanovsky, V.E., 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. J. Geophys. Res. 116. doi:10.1029/2011JG001666

Kokelj, S.V., Jorgenson, M.T., 2013. Advances in Thermokarst Research: Recent Advances in Research Investigating Thermokarst Processes. Permafr. Periglac. Process. 24, 108–119. doi:10.1002/ppp.1779

Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L., Coutts, R., 2009. Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada. Permafr. Periglac. Process. 20, 173–184. doi:10.1002/ppp.642

Kokelj, S.V., Tunnicliffe, J., Lacelle, D., Lantz, T.C., Chin, K.S., Fraser, R., 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. Glob. Planet. Change 129, 56–68. doi:10.1016/j.gloplacha.2015.02.008

Labrecque, S., Lacelle, D., Duguay, C.R., Lauriol, B., Hawkings, J., 2009. Contemporary (1951-2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: Remote sensing, numerical modeling, and stable isotope analysis. Arctic 225–238.

Lafrenière, M.J., Louiseize, N.L., Lamoureux, S.F., 2017. Active layer slope disturbances affect seasonality and composition of dissolved nitrogen export from High Arctic headwater catchments. Arct. Sci. 3, 429–450. doi:10.1139/as-2015-0009

Lamhonwah, D., Lafrenière, M.J., Lamoureux, S.F., Wolfe, B.B., 2017. Multi-year impacts of permafrost disturbance and thermal perturbation on High Arctic stream chemistry. Arct. Sci. 3, 254–276. doi:10.1139/as-2016-0024

Lantz, T.C., Kokelj, S.V., 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophys. Res. Lett. 35. doi:10.1029/2007GL032433

Lantz, T.C., Turner, K.W., 2015. Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. J. Geophys. Res. Biogeosciences 120, 513–524. doi:10.1002/2014JG002744

Lauriol, B., Duguay, C.R., Riel, A., 2002. Response of the Porcupine and Old Crow rivers in northern Yukon, Canada, to Holocene climatic change. The Holocene 12, 27–34. doi:10.1191/0959683602hl517rp

Mackay, J.R., 1997. A full-scale field experiment (1978–1995) on the growth of permafrost by means of lake drainage, western Arctic coast: a discussion of the method and some results. Can. J. Earth Sci. 34, 17–33.

Mackay, J.R., 1992. Lake stability in an ice-rich permafrost environment: examples from the western arctic coast., in: Robarts, R.D., Bothwell, M.L. (Eds.), Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management, National Hydrology Research Institute Symposium Series. Environment Canada, Saskatoon, pp. 1–6.

Mackay, J.R., 1988. Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie. Geol. Surv. Can. 88–1D, 83–90.

Morlan, R.., 1980. Taphonomy and archaeology in the Upper Pleistocene of the northern Yukon Territory: a glimpse of the peopling of the New World, Mercury series / National Museum of Man Paper / Archaeological Survey of Canada; no. 94 Mercury series.

Morlan, R.E., 2003. Current perspectives on the Pleistocene archaeology of eastern Beringia. Quat. Res. 60, 123–132. doi:10.1016/S0033-5894(03)00070-X

Myers-Smith, I.H., Elmendorf, S.C., Beck, P.S.A., Wilmking, M., Hallinger, M., Blok, D., Tape, K.D., Rayback, S.A., Macias-Fauria, M., Forbes, B.C., Speed, J.D.M., Boulanger-Lapointe, N., Rixen, C., Lévesque, E., Schmidt, N.M., Baittinger, C., Trant, A.J., Hermanutz, L., Collier, L.S., Dawes, M.A., Lantz, T.C., Weijers, S., Jørgensen, R.H., Buchwal, A., Buras, A., Naito, A.T., Ravolainen, V., Schaepman-Strub, G., Wheeler, J.A., Wipf, S., Guay, K.C., Hik, D.S., Vellend, M., 2015. Climate sensitivity of shrub growth across the tundra biome. Nat. Clim. Change 5, 887–891. doi:10.1038/nclimate2697

Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Macias-Fauria, M., Sass-Klaassen, U., Lévesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L.S., Weijers, S., Rozema, J., Rayback, S.A., Schmidt, N.M., Schaepman-Strub, G., Wipf, S., Rixen, C., Ménard, C.B., Venn, S., Goetz, S., Andreu-Hayles, L., Elmendorf, S., Ravolainen, V., Welker, J., Grogan, P., Epstein, H.E., Hik, D.S., 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environ. Res. Lett. 6, 045509. doi:10.1088/1748-9326/6/4/045509

Porter, T.J., Pisaric, M.F.J., 2011. Temperature-growth divergence in white spruce forests of Old Crow Flats, Yukon Territory, and adjacent regions of northwestern North America. Glob. Change Biol. 17, 3418–3430. doi:10.1111/j.1365-2486.2011.02507.x

Riordan, B., Verbyla, D., McGuire, A.D., 2006. Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. J. Geophys. Res. Biogeosciences 111. doi:10.1029/2005JG000150

Roy-Léveillée, P., Burn, C.R., 2010. Permafrost conditions near shorelines of oriented lakes in Old Crow Flats, Yukon Territory, in: Conference Proceedings of GEO. pp. 1509–1516.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., Olefeldt, D., Romanovsky, V.E., Schaefer, K., Turetsky, M.R., Treat, C.C., Vonk, J.E., 2015. Climate change and the permafrost carbon feedback. Nature 520, 171–179. doi:10.1038/nature14338

Shur, Y.L., Jorgenson, M.T., 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafr. Periglac. Process. 18, 7–19. doi:10.1002/ppp.582

Smith, L.C., Sheng, Y., MacDonald, G.M., Hinzman, L.D., 2005. Disappearing Arctic Lakes. Science 308, 1429.

Tondu, J.M.E., Turner, K.W., Wolfe, B.B., Hall, R.I., Edwards, T.W.D., McDonald, I., 2013. Using Water Isotope Tracers to Develop the Hydrological Component of a Long-Term Aquatic Ecosystem Monitoring Program for a Northern Lake-Rich Landscape. Arct. Antarct. Alp. Res. 45, 594–614. doi:10.1657/1938-4246-45.4.594

Toniolo, H., Kodial, P., Hinzman, L.D., Yoshikawa, K., 2009. Spatio-temporal evolution of a thermokarst in Interior Alaska. Cold Reg. Sci. Technol. 56, 39–49. doi:10.1016/j.coldregions.2008.09.007

Turner, K.W., Edwards, T.W.D., Wolfe, B.B., 2014a. Characterising Runoff Generation Processes in a Lake-Rich Thermokarst Landscape (Old Crow Flats, Yukon, Canada) using $\delta^{18}O$, $\delta^{2}H$ and d-excess Measurements: Characterising Runoff with Water Isotope Tracers in Old Crow Flats, Yukon. Permafr. Periglac. Process. 25, 53–59. doi:10.1002/ppp.1802

Turner, K.W., Wolfe, B.B., Edwards, T.W.D., 2010. Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. J. Hydrol. 386, 103–117. doi:10.1016/j.jhydrol.2010.03.012

Turner, K.W., Wolfe, B.B., Edwards, T.W.D., Lantz, T.C., Hall, R.I., Larocque, G., 2014b. Controls on water balance of shallow thermokarst lakes and their relations with catchment characteristics: a multi-year, landscape-scale assessment based on water isotope tracers and remote sensing in Old Crow Flats, Yukon (Canada). Glob. Change Biol. 20, 1585–1603. doi:10.1111/gcb.12465

Wolfe, B.B., Humphries, M.M., Pisaric, M.F., Balasubramaniam, A.M., Burn, C.R., Chan, L., Cooley, D., Froese, D.G., Graupe, S., Hall, R.I., others, 2011. Environmental change and traditional use of the Old Crow Flats in northern Canada: an IPY opportunity to meet the challenges of the new northern research paradigm. Arctic 64, 127.

Wolfe, B.B., Turner, K.W., 2008. Near-record precipitation causes rapid drainage of Zelma Lake, Old Crow Flats, northern Yukon Territory. Meridian Spring Edition, 7–12.

Yoshikawa, K., Hinzman, L.D., 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near council, Alaska. Permafr. Periglac. Process. 14, 151–160. doi:10.1002/ppp.451

Zazula, G.D., Duk-Rodkin, A., Schweger, C.E., Morlan, R.E., 2004. Late Pleistocene chronology of Glacial Lake Old Crow and the north-west margin of the Laurentide ice sheet, in: Quaternary Glaciations-Extent and Chronology Part II: North America. Elsevier London, pp. 347–362.

Chapter 2: Intended for publication in Arctic Science.

# Identifying spatial variation in runoff generation processes across a lake-rich permafrost landscape using water chemistry and isotope tracers (Old Crow Flats, Yukon).

D. Hughes[1] and K.W. Turner[2]

[1]Department of Earth Science, Brock University, St. Catharines, Ontario, Canada, [2]Department of Geography and Tourism Studies, Brock University, St. Catharines, Ontario, Canada

## 2.1 Introduction

Lake-rich permafrost landscapes are widespread across northern regions and are physically dynamic and sensitive to climate change. Lakes are formed from thermokarst processes where ice-rich permafrost has subsided and surface water has subsequently accumulated. Small ponds continue to coalesce until shallow lakes are formed (Rampton, 1988). The rate of permafrost thaw is increased by local climate (i.e., increasing temperature and precipitation) and disturbances (e.g., forest fires). Thermokarst lake fluctuations have been widely studied using multiple approaches to identify changes in lake area, abundance, as well as lake drainage events across Arctic permafrost regions (Yoshikawa and Hinzman, 2003; Smith et al., 2005; Jorgenson et al., 2006; Riordan et al., 2006; Carroll et al., 2011; Jones et al., 2011; Bouchard et al., 2013; Lantz and Turner, 2015). These studies have found variability in lake stability based on specific landscape characteristics (permafrost, climate, vegetation). Lake area stability has been documented as increasing (Jorgenson et al., 2006; Jones et al., 2011), remaining stable (Riordan et al., 2006), and decreasing through evaporation or rapid drainage (Smith et al., 2005; Turner et al., 2010; Lantz and Turner, 2015). One mechanism of lake drainage, through lateral channels, is rarely observed directly, and typically by chance (Mackay, 1988; Marsh and

Neumann, 2001; Turner et al., 2010, 2014a). Thus, our ability to track lake drainages has relied on the use of remotely sensed images after the fact (Lantz and Turner, 2015), and has created difficulty in identifying resulting changes in hydrological conditions across the drainage network.

Research investigating the chemical properties of thermokarst lakes (Manasypov et al., 2014; Balasubramaniam et al., 2015) and their isotope characteristics (Turner et al., 2010; Tondu et al., 2013) show major influences on the hydrology from the surrounding landscape features. Manasypov et al. (2014) studied thermokarst lakes across Siberia, identifying influences on the water chemistry. They found that leaching from surrounding peat had an influence on solutes within the thermokarst lakes studied, but that latitudinal position had the greatest influence. Lake water from thermokarst lakes has also been found to be highly correlated with surrounding landscape characteristics determined from studies completed characterizing lakes via their isotopic enrichment (Turner et al., 2010). Turner et al. (2010) found that thermokarst lakes can be snowmelt-dominated, rainfall-dominated, groundwater-influenced, evaporation-dominated, or drained. This variability in source water balance alters the characteristics of the hydrology through catchment features such as shrub cover or tundra, which in turn can alter lake water chemistry (Balasubramaniam et al., 2015). Fluctuations in river water chemistry and sediment load has also been observed across the Arctic relating to local permafrost thaw and erosion (Walvoord and Striegl, 2007; Toniolo et al., 2009). These studies highlight the importance of landscape characteristics on lake hydrology, however, it is unclear how lakes are influencing the drainage network that they export water to.

Old Crow Flats (OCF) is a lake-rich permafrost landscape encompassing ~8700 water bodies where previous studies have examined spatial and temporal variability in hydrological conditions (Turner et al., 2010, 2014b; Lantz and Turner, 2015). Recent studies conducted during the International Polar Year (IPY) investigated environmental change and traditional use of OCF coupled with local community members involvement (Wolfe and Turner, 2008; Wolfe et al., 2011; Porter and Pisaric, 2011). This research and community knowledge identified changes in lake and river water levels, river bank erosion and increased vegetation growth (Wolfe et al., 2011). These changes also coincide with a warming climate over recent decades (Porter and Pisaric, 2011) and have community members concerned about the continuation of future landscape change. Lake hydrological conditions are spatially and seasonally variable based on catchment characteristics, such as vegetation cover and soil properties that influence the quality and quantity of source water inflow into nearby rivers (Turner et al., 2010, 2014b). Water isotope compositions have been utilized to characterize runoff generation processes for the southern reach of the Old Crow River during 2007-09 (Turner et al., 2014a). However, lake-to-river connectivity throughout the majority of OCF remains uncharacterized, and additional parameters must be examined to assess the influence of upstream runoff generation processes on downstream environments. Here, we use water chemistry and isotope signatures to capture the spatial variability in lake-to-river connections across OCF on a seasonal and inter-annual timescale. Seasonal and annual fluctuations in temperature and precipitation are expected to influence the number of lake-to-river connections along with runoff processes controlling the hydrology. Landscape changes such as lake drainage events and retrogressive thaw slumps could also impact downriver hydrology. Results show spatial variability in landscape influences on the hydrology, and could be continued as a monitoring tool across OCF for landscape changes.

## 2.2 Study Site

Old Crow Flats (OCF) is a lake-rich thermokarst landscape located in northern Yukon, Canada (Figure 2.1). It encompassed Glacial Lake Old Crow when the Laurentide Ice Sheet (LIS) bordered the flats to the east during the Wisconsinan glaciation. Prior to this, the Old Crow River flowed to the Porcupine River which flowed east to the Mackenzie Delta. The LIS blocked the outflow of the Porcupine River leading to the formation of Glacial Lake Old Crow, which flooded non-glaciated lowlands in the OCF surrounded by the British, Richardson, Ogilvie and Old Crow mountain ranges. The LIS retreated until the late Wisconsinan glacial advance when the water level peaked and, caused erosion across the Upper Ramparts to the west and catastrophic drainage between 16.4 and 14.9 ka BP, leaving behind silt and clay rich sediments (Morlan, 2003; Zazula et al., 2004). Thermokarst ensued during the Holocene as ice-rich permafrost subsided and water bodies formed.

Today, OCF is estimated to contain over 8700 thermokarst lakes and ponds (Lantz and Turner, 2015), which vary in depth (0.5-6 m) and area (1-3700 ha; Labrecque et al., 2009). The Old Crow River and its tributaries are incised in periglacial sediments of former glacial lake Old Crow (Morlan, 1980; Lauriol et al., 2002). The area is within continuous permafrost (Hughes, 1972). Changes in lake area and water level are prevalent with noticeable drained lake basins and erosion channels across the landscape. Lakes are perched above river flow in OCF, contributing water to the Old Crow River drainage network. The Old Crow River connects to the Porcupine River just north of Old Crow and continues towards Alaska, USA via the Yukon River. Local community members of Old Crow have observed landscape changes including lower lake levels, river bank erosion and increasing winter temperatures (Wolfe et al., 2011).

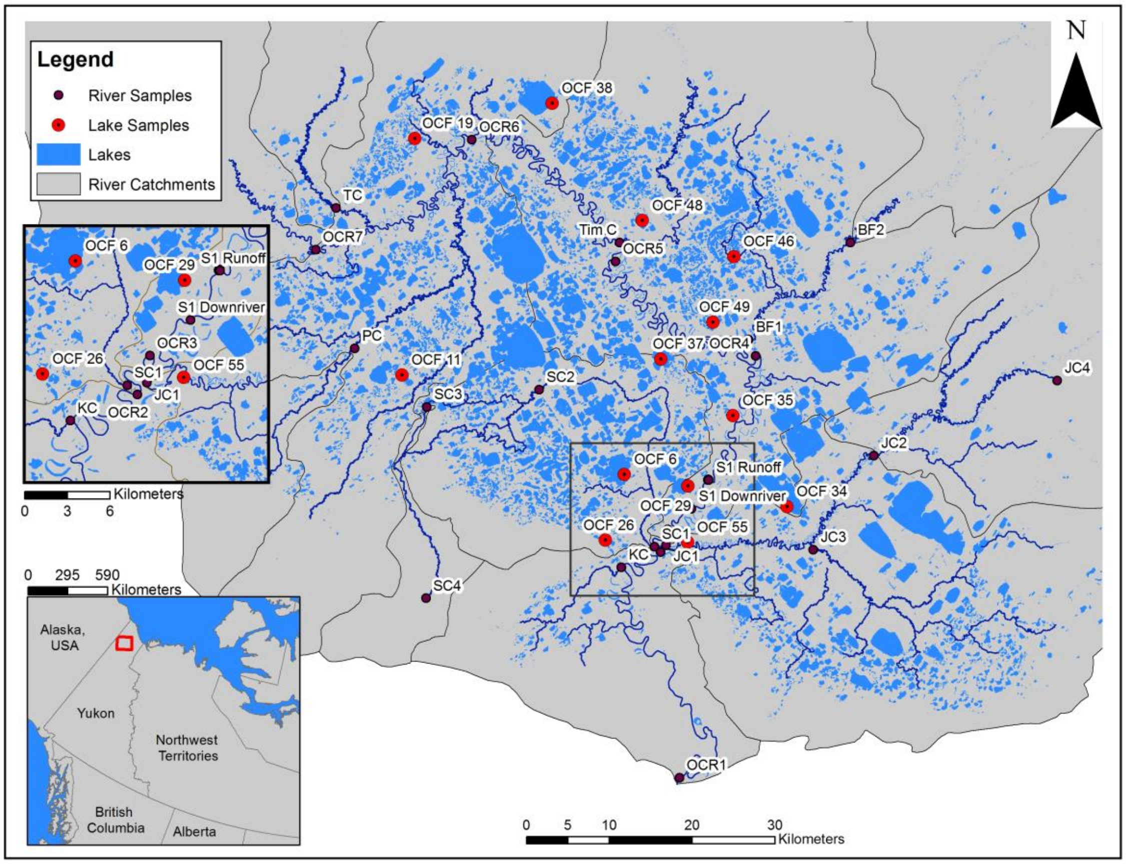



*Figure 2.1. River and lake sampling sites across Old Crow Flats during July 2015 and May and July 2016. River catchments are delineated by the dark grey sections on the map.*

## 2.3 Methods

### 2.3.1 Sample Collection and Analysis

A network of water sampling sites throughout the OCF drainage system was established to evaluate seasonal and inter-annual variation in the spatial patterns of upstream runoff generation processes including lake-river hydrological connectivity and rainfall versus snowmelt. Water was sampled during late July 2015 and 2016 ($24^{th}$-$25^{th}$ and $26^{th}$-$29^{th}$, respectively) from a helicopter, and a smaller number of samples (15 river and 1 lake sample) taken in May 2016 ($26^{th}$-$27^{th}$) when water levels were high enough to access sites by boat. Four litre carbuoys and 1 L high-density polyethylene environmental sample (HDPE) bottles were used for sampling and transport of samples to Old Crow where they were prepared for shipment and lab analysis. River sites were sampled at 23 sites along ~350 km of the Old Crow River and its major tributaries (Figure 2.1). Locations were selected for the purpose of tracking downstream transitions in runoff generation processes. Site names include acronyms of the creek or river names and numbers representing their order upstream (e.g. river numbering is from highest upriver to lowest downriver: e.g. OCR7 – OCR1). Water was also sampled at 13 lake sites which have been monitored in collaboration with Parks Canada since 2007 (Tondu et al., 2013).

*Figure 2.2.The collection of water samples from throughout Old Crow Flats. Photos by Dr. Kevin Turner*

Water samples were stored in a fridge at $4^{o}C$ and pre-processed in Old Crow. Samples were processed for a suite of water chemistry parameters including total nitrogen (TN), total phosphorus (TP), pH, turbidity (Turb), conductivity, alkalinity (Alk) and total gran alkalinity and were pre-screened through a 200 µm mesh to remove any large particles. Major ions (Mg, Na, $SO_4$, $SiO_2$, K, Ca, Cl), nitrates ($NO_2$ + $NO_3$), total dissolved phosphorus (TDP), total dissolved nitrogen (TDN), dissolved inorganic and organic carbon (DIC/DOC) were pre-screened through a 200 µm mesh and filtered through 0.45 µm acetate filters. Sample analysis was completed at the Biogeochemical Analytical Service Laboratory (BASL) located at the University of Alberta.

Samples sent to BASL were also filtered through 0.45-µm acetate filters and stored in 2-ml glass vials for water isotope composition ($\delta^2H$, $\delta^{18}O$) analysis to evaluate the relationship between the heavy stable isotopes. BASL uses a liquid isotope analyzer following the absorption technique “Off-Axis Integrated Cavity Output Spectroscopy” (OA-ICOS) with a precision of ±2.0‰ for $\delta^2H$ and ± 0.2‰ for $\delta^{18}O$, respectively. Isotopic compositions are expressed as δ values, which represent per mil (‰) from Vienna Standard Mean Ocean Water (VSMOW). The data was normalized to -428‰ and -55.5‰ ($\delta^2H$ and $\delta^{18}O$ respectively) to account for Standard Light Antarctic Precipitation (SLAP) (Coplen, 1996).

Lake and river water isotope compositions were plotted on an isotope framework that includes the Global Meteoric Water Line (GMWL) described by (Craig, 1961) as $\delta^2H = 8\delta^{18}O + 10$, and the local evaporation line (LEL). The GMWL represents the global ratio of oxygen and hydrogen in terrestrial waters, while the position of the LEL and its extension at a slope of 4-6 from the GMWL represents the kinetic isotope fractionation of surface waters as they undergo evaporation. The intersection of the LEL and the GMWL represents the average annual isotope composition of precipitation ($\delta_P$). The LEL has been determined in the past using a class-A desiccation pan maintained during ice-free seasons at the Old Crow airport from 15 June to 21 September 2007 (Turner et al., 2010), and August 2010 (Tondu et al., 2013). Water was added to the evaporation pan weekly when sampled, which maintained representation of a lake at isotopic steady-state ($\delta_{SSL}$) where water input was equal to water loss by evaporation. The terminus of the LEL ($\delta^*$) represents a lake approaching complete desiccation, and is calculated from the equation by (Gonfiantini, 1986) using the evaporation pan. The position of lake isotope compositions, when superimposed on the isotope framework, provides key insight of the relative importance of the varying hydrological controls.

Water isotope compositions were used to calculate deuterium-excess (d-excess), a single metric representing the relative importance of evaporation. Deuterium-excess represents the separation of each $\delta^2H$ and $\delta^{18}O$ value from the GMWL (d-excess = $\delta^2H - 8*\delta^{18}O$; (Dansgaard, 1964)). The values represent the offset from the GMWL indicating an increased evaporative enrichment in the water sample. These values present a single variable, which can be used in other spatial and statistical methods for interpretation.

Additional parameters used to investigate lake-to-river connectivity included total suspended solids (TSS) and chlorophyll a (Chl *a*), which were identified using Whatman GF/C (1.2 µm) and GF/F (0.6 µm) filters, respectively. These filters were sealed in aluminum foil and frozen for shipment to Brock University for analysis. TSS filters, used to identify possible increases in river bank erosion or discharge, were pre-burned at 550$^{o}$C for 4 hours prior to filtering which removed any contaminants. After filtering, filters were dried at 95$^{o}$C for 24 hours to remove moisture, and then weighed for total suspended solids.

Meteorological data collected by Environment Canada at the Old Crow Airport was used in this study to identify possible influences on isotope signatures from across OCF. Precipitation and temperature changes were monitored to evaluate associated influence on water chemistry and isotope parameters. The Old Crow Airport is located approximately 25 kilometers south of the southern boundary of OCF. The precipitation and temperature data for OCF was estimated from the stations within Old Crow. Daily total precipitation was collected and summed for each month to highlight annual variability. Daily temperature data was also plotted to identify annual variability across sample periods.

Water chemistry data was analyzed using principal component analysis (PCA) to evaluate correlations among parameters for each site. PCA reduces the dimensionality of the data while retaining as much of the variation as possible in the dataset. The data was plotted on a PCA biplot so the first few axes retain the highest amount of variation present in the entire dataset (Jolliffe, 2002). This allows for correlation between eigenvalues and all the sample points in the data set. The PCA was created using the vegan library (version 2.4-3; Oksanen et al., 2017) in Rstudio and running an unconstrained Redundancy Analysis (RDA). The resulting principal component axes are validated with the use of a scree plot, which displays the variance of each principal component. Then the broken stick methodology is used, which represents a random (null) model and calculates a set of expected values, principal components which fall above the null model are retained (Appendix A).

## 2.4 Results

### 2.4.1 Meteorological Data

Data collected from the Old Crow Airport station indicate that precipitation was variable during the two years of sampling and was plotted from September to August, highlighting snowmelt and rainfall influence on the two sampling seasons (Figure 2.3). The largest variability is found in September (~2mm in 2015, ~72mm in 2016). Winter precipitation over the two sampling years had less variation than the spring, summer, and fall months.

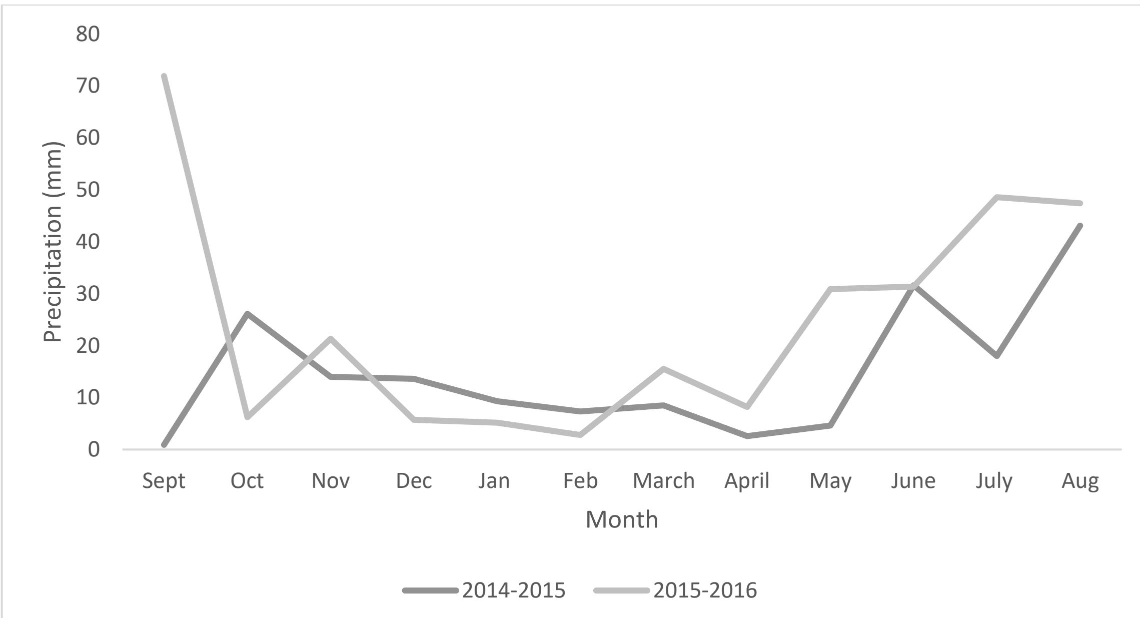



*Figure 2.3. Monthly precipitation totals for Old Crow Flats from Sept. – Aug. 2014-2015 and 2015-2016. Data collected from Old Crow which is ~25km south of OCF.*

Temperature data was similar during the two years of study (Figure 2.4). The highest temperatures reaching (~20$^{o}$C) during the late summer months when the samples were collected. During the winter months, there was more annual variability in average temperatures (-45 to -20$^{o}$C), but winter temperatures in 2016 reaching as high as (-5$^{o}$C).

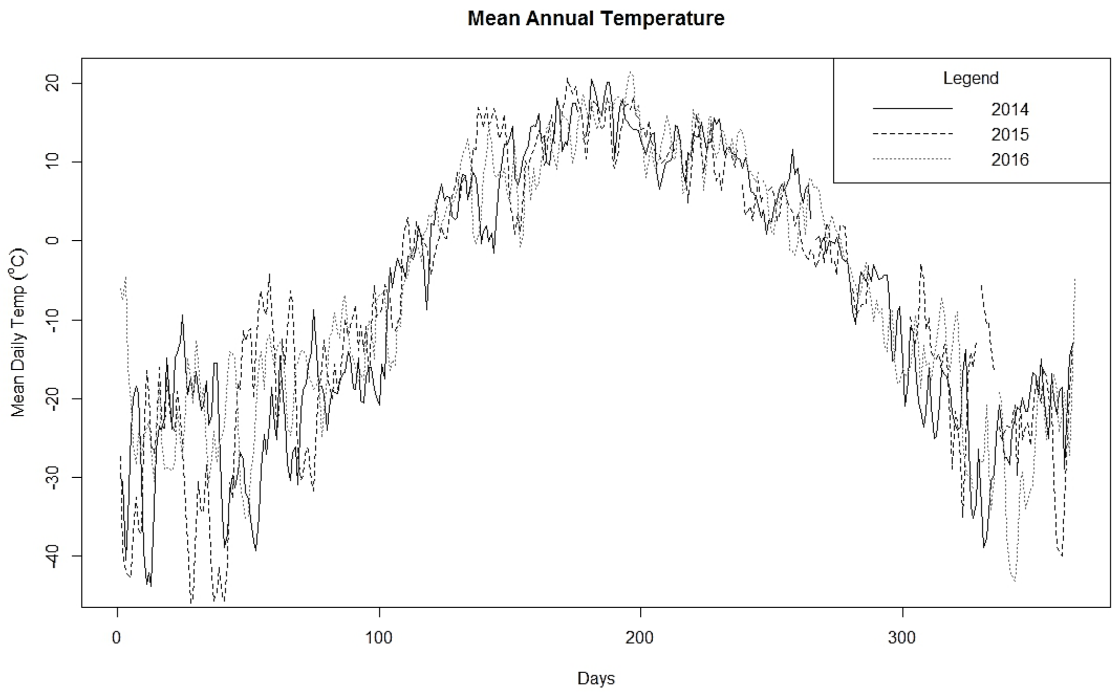



*Figure 2.4. Annual temperature for Old Crow Flats from 2014-2016. Data collected from the City of Old Crow located ~25km south of OCF.*

### 2.4.2 Isotopic Analysis

The isotope composition of precipitation generally plots along the global meteoric water line (GMWL) as stated by Craig (1961) as $\delta^2H = 8\delta^{18}O + 10$. The position along the GMWL is dependant on the distillation history of the atmospheric moisture as well as seasonal factors such as snow falling closer to the isotopically depleted section of the GMWL compared to rain. For OCF, the LEL was calculated using weekly samples from an evaporation pan maintained for four ice-free seasons (2007-2010) (Tondu et al., 2013). Rainfall has higher values than $\delta_P$, whereas snowmelt has lower values. The isotope composition of lake and river samples are superimposed on this isotope framework to evaluate the relative importance of the hydrological controls. For instance, sample values plotting above or below the LEL are influenced more strongly by rainfall or snowmelt, respectively. Samples plotting further along the LEL undergo greater water loss from evaporation than those plotting closer to the GMWL. River isotope values plotted on the isotope framework show the relative importance of the hydrological controls including lake water outflow.

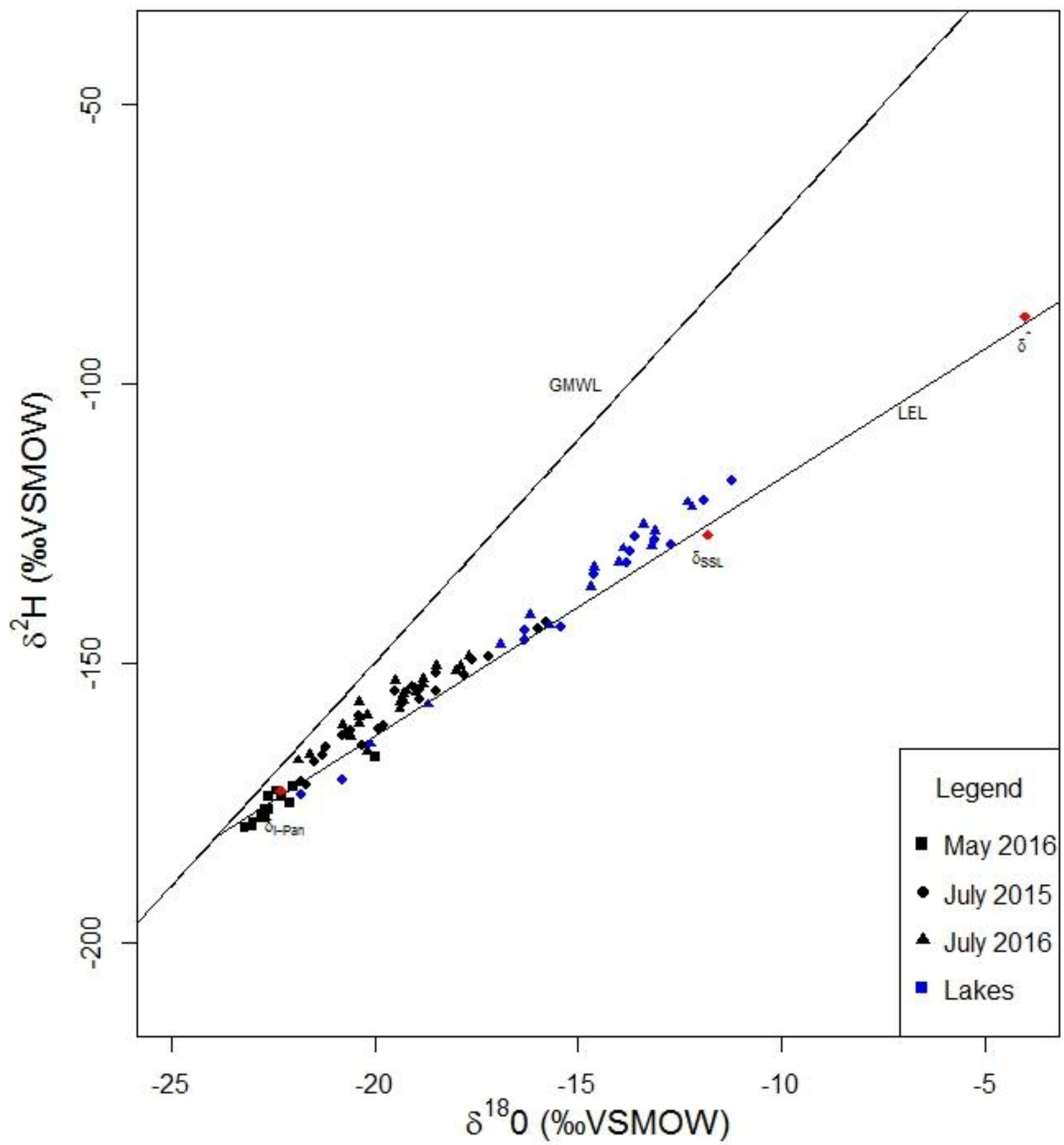



*Figure 2.5. River and creek ($\delta^2H$ and $\delta^{18}O$) isotope data from all sampling dates based on Vienna Standard Mean Ocean Water (%VSMOW). Values are plotted against the Global Meteoric Water Line (GMWL) and the Local Evaporation Line (LEL) calculated utilizing a local desiccation pan. Calculated LEL points are displayed in red.*

All lake and river samples from the three sampling campaigns in OCF were superimposed on the isotope framework to show seasonal and annual variability across OCF (Figure 2.5). Lake samples plot higher along the LEL, falling closer to $\delta_{SSL}$ than river sites, which plot closer to ($\delta_P$), indicating greater evaporation and less of an influence from non-lake water runoff. The seasonal variation in all isotope concentrations was driven by the spring snowmelt, with samples from May 2016 plotting closer to the GMWL than July samples. Snow sampled during previous studies consistently had the lowest isotope values found in OCF (ranging from -31.3‰ to -22.2‰ and -242‰ to -193‰ for $\delta^{18}O$ and $\delta^2H$, respectively; Turner et al., 2010, 2014a, 2014b). Inter-annual variability in isotope signatures show little change across July 2015-2016. Rivers plot in similar locations along the LEL with increasing inflow of evaporated water at higher-order river sampling locations. Lakes across OCF span the hydrological gradient from positive to negative water balances (Tondu et al., 2013) and also appear stable across inter-annual sampling. The lakes with the lowest values (OCF48, 55), which plot lower on the LEL across both years indicating a stable lake system, which has relatively high runoff that offsets the effects of evaporation. These lakes display similar evaporative enrichment from previous work where OCF55 is snowmelt dominated with low evaporative enrichment (Turner et al., 2014b). OCF48 is rainfall dominated (Turner et al., 2014b) and gets consistent inflow of shallow groundwater from a neighbouring upland (MacDonald et al., 2012). Conversely, lakes OCF6 and 46 plot above the $\delta_{SSL}$ across both years and highlight increased evaporative enrichment. OCF6 and 46 coincide with previous research, containing higher levels of evaporative enrichment (Turner et al., 2010).

A subset of river water samples was obtained during May 2016 to enhance our understanding of seasonal variation in hydrological conditions and lake-river connectivity across OCF (Figure 2.6). Samples collected during this time captured higher snowmelt, which is usually complete by late May causing the river to be at its highest annual level. Lake water levels are also usually at their highest during this time, which allows for greater connection to drainage channels. The isotope signatures from May highlight the increased connectivity and melt water flowing through OCF with minimal evaporation. This indicates that the source water is predominantly snowmelt and surface runoff dominated.

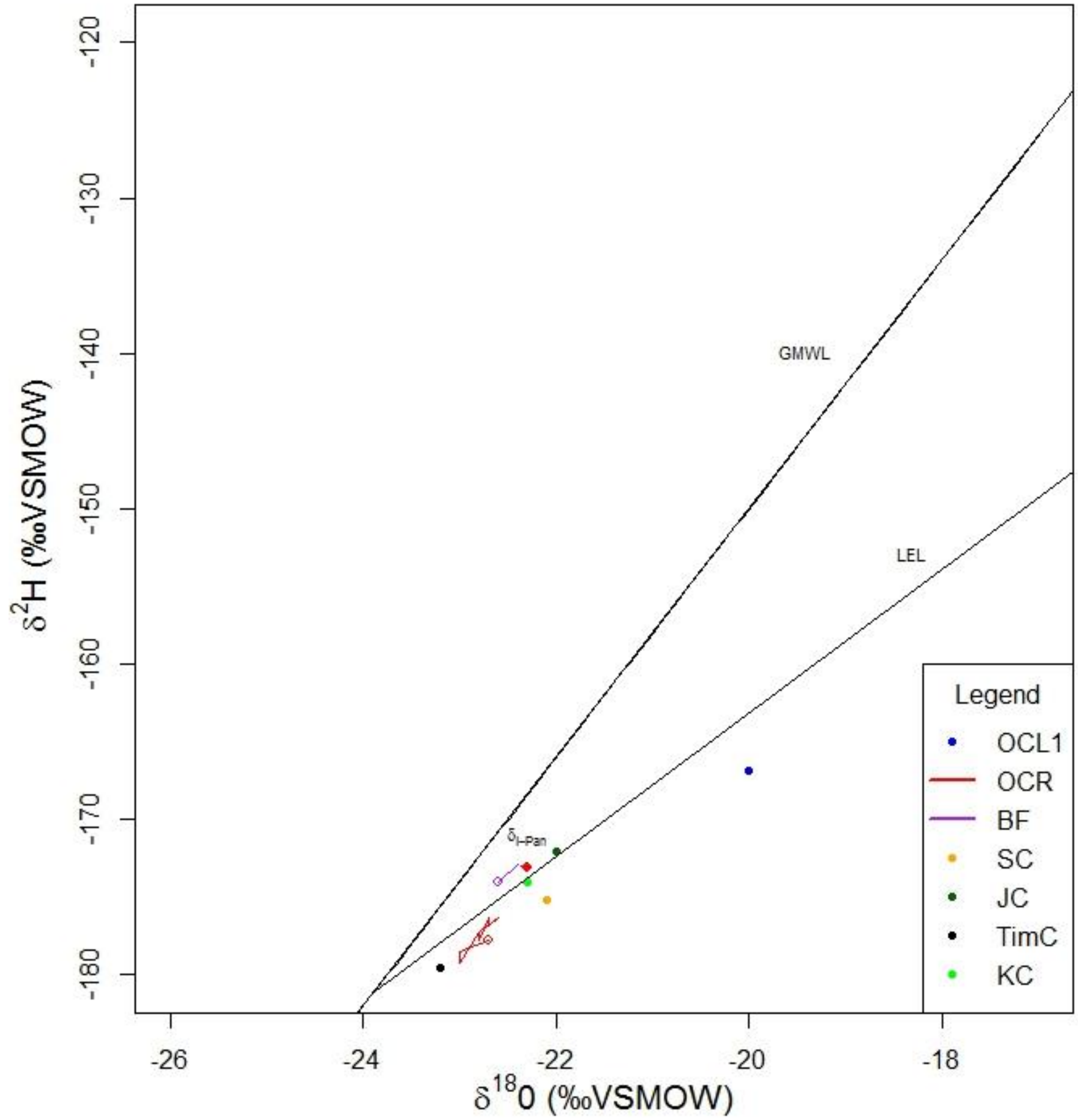



*Figure 2.6. River and creek ($\delta^2H$ and $\delta^{18}O$) isotope data from May 2016 based on Vienna Standard Mean Ocean Water (%VSMOW). Headwaters of each river tributary are depicted by colored hollow circles at the start of each line. Sites where a single river sample was taken from the tributary as well as the one lake sample (OCL1) are displayed by a single point plotted on the isotope framework of Figure 2.5. Legend site codes are based on table 1.1.*

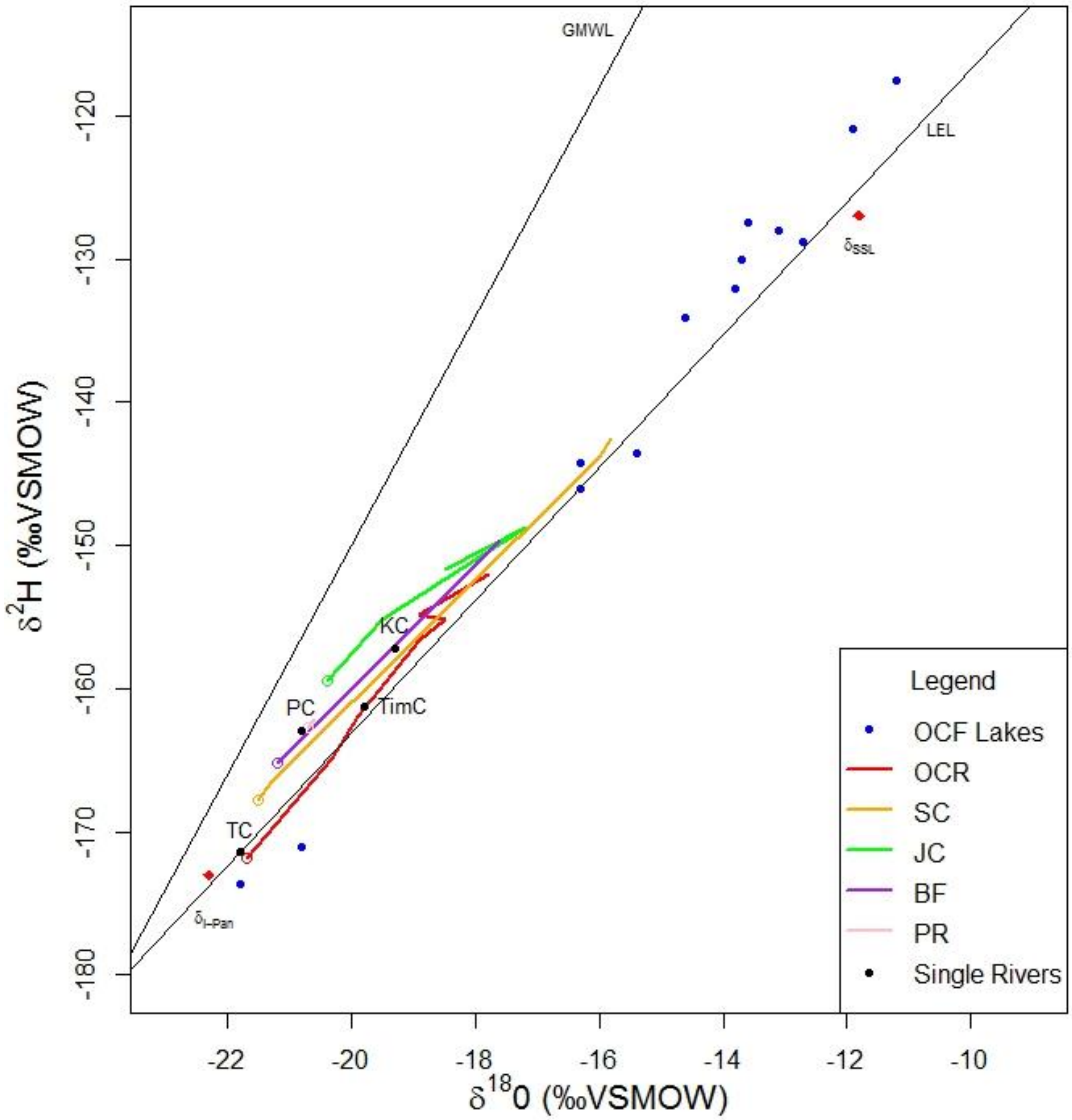



*Figure 2.7. River and creek ($\delta^2H$ and $\delta^{18}O$) isotope data from July 2015 based on Vienna Standard Mean Ocean Water (%VSMOW). Headwaters of each river tributary are depicted by colored hollow circles at the start of each line. Sites with a single river sample for the tributary are displayed with a single black point. Isotope data is plotted on the framework as displayed in Figure 2.5. Legend site codes based on table 1.1.*

Samples collected 24-25 July 2015 had higher average $\delta^2$H and $\delta^{18}$O isotope signatures than in spring (-151.2‰ to -175.7‰, -17.8‰ to -22.5‰ for $\delta^2$H and $\delta^{18}$O from July to May, respectively; Figure 2.7). The lowest tributary values along the LEL tend to be lower order northern tributaries such as Thomas Creek (TC) (-172‰ and -21.8‰, for

$\delta^2H$ and $\delta^{18}O$, respectively). Downstream isotope trajectories increase as more lake water outflow is exported to the drainage network. This pattern is most evident in Schaeffer Creek (SC) which has the highest isotope values at its mouth at the Old Crow River and the greatest overall downriver shift (-168‰ to -145‰ and -21.6‰ to -15.8‰, for $\delta^2H$ and $\delta^{18}O$, respectively).

Evaluating the relative importance of evaporation on the hydrology of each site was completed using spatial analysis of deuterium excess (d-excess) values which integrates $\delta^2H$ and $\delta^{18}O$ values into a single metric ($\delta^2H - 8*\delta^{18}O$; (Dansgaard, 1964)). Deuterium-excess represents the level of separation of $\delta^2H$ and $\delta^{18}O$ from the GMWL and its evaporative enrichment. There is a strong spatial variability in river water d-excess shown by mapping river sample changes along each tributary where the darker blues represent increasing evaporative enrichment. Upstream values tend to have lower d-excess than the southern tributaries (SC, JC), and southern OCR (Figure 2.9). This pattern illustrates the downstream increasing export of lake water. This increase is likely from lake-to-river connections where most lake sites plot further along the LEL closer to $\delta_{SSL}$ indicating evaporative enrichment compared to river sites. Plotting closer to $\delta_P$, (OCF48 and 55 are exceptions), indicates that precipitation and runoff to lakes effectively offsets evaporative loss in these lakes. Results display a distinction in isotope values between northern and southern positioned tributaries in OCF. Southern tributaries have higher proportions of lake water, which is affected more by evaporation (low d-excess) compared to the northern tributaries.

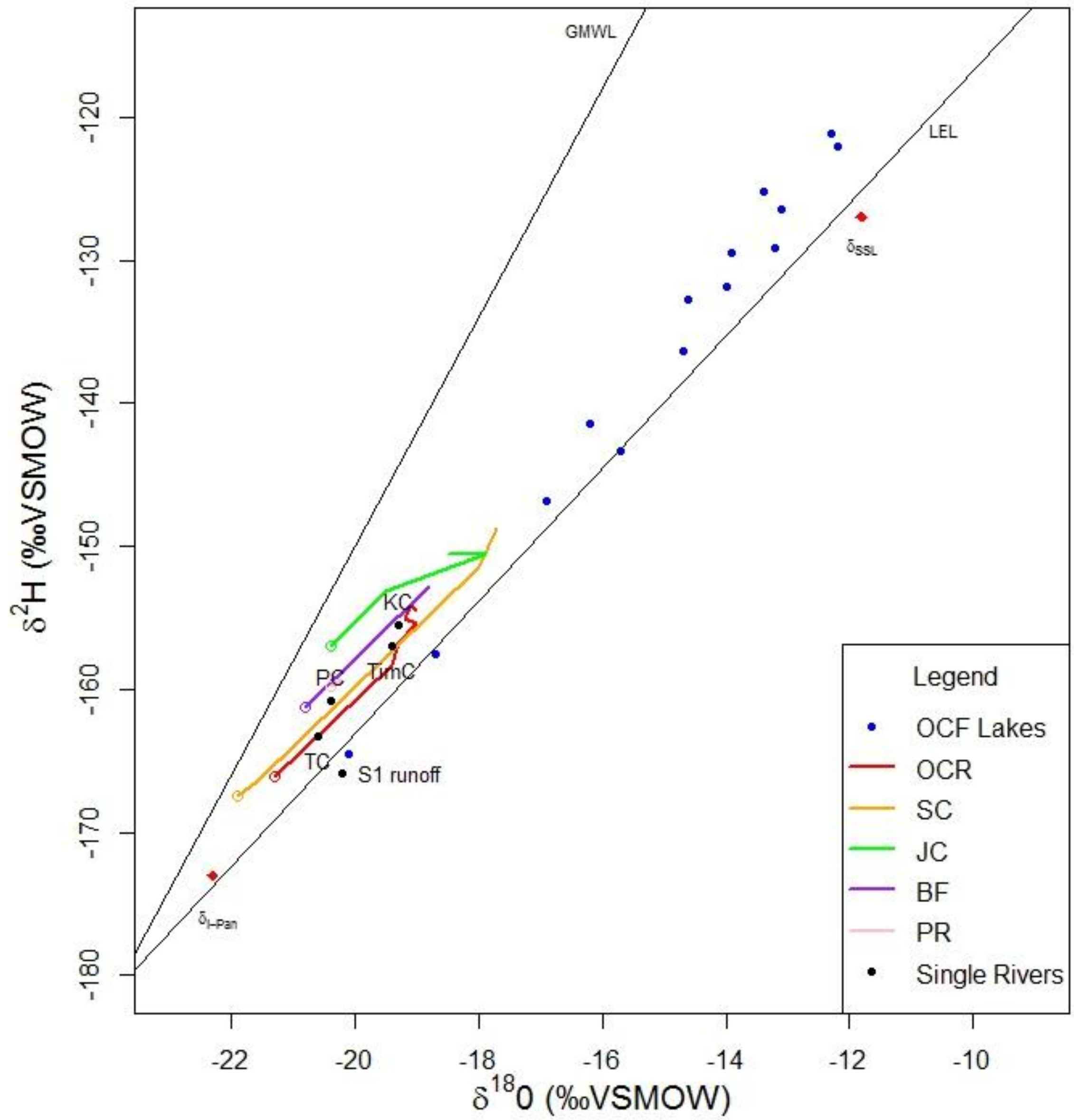



*Figure 2.8. River and creek ($\delta^2H$ and $\delta^{18}O$) isotope data from July 2016 based on Vienna Standard Mean Ocean Water (%VSMOW). Headwaters of each river tributary are depicted by colored hollow circles at the start of each line. Sites where a single river sample was taken from the river tributary are displayed with a single black point. Isotope data is plotted on the framework as displayed in Figure 2.5. Legend site codes based on table 1.1.*

Resampling sites during July 2016 allowed for comparing hydrological responses to varying inter-annual meteorological conditions and associated runoff generation processes. Creek and river sites show increasing $\delta^2$H and $\delta^{18}$O values downstream (mean change of 9.14‰ and 2.12‰ for $\delta^2$H and $\delta^{18}$O respectively; Figure 2.8). Values are higher for lakes since they undergo more prolonged evaporation, with OCF6 and 46 showing the greatest evaporative enrichment, plotting above the $\delta_{SSL}$ and OCF48 and 55 are the lowest lakes along the LEL. Headwater samples from all rivers and tributaries have similar isotope signatures from 2015 to 2016 (spanning from -170‰ to -160‰ and -22‰ to -20‰, for $\delta^2H$ and $\delta^{18}O$ respectively) but higher-order river samples (JC1, SC1, KC, BF1, OCR1) have lower values during 2016 (spanning from -155‰ to -150‰, -19‰ to -18‰ for $\delta^2H$ and $\delta^{18}O$, respectively) than in 2015 (from -150‰ to -140‰, -18‰ to -16‰ for $\delta^2H$ and $\delta^{18}O$, respectively). Deuterium values from all lake and river samples between July 2015 and 2016 are found to be statistically different (p-value = 0.03266; Table 2.1) however $\delta^{18}O$ values are not (p-value = 0.60044). Deuterium-excess river values (Figure 2.9) reflect a similar overall decrease in maximum evaporative enrichment across OCF and are statistically different (-15 to -7.8 from 2015 to 2016; p-value = 0.00034). Lake d-excess values also decreased in evaporative enrichment (-18.2 to -16.9 from 2015 to 2016; p-value = 0.146968). Large shifts in evaporative enrichment are noticeable from the furthest headwater sites (TC, OCR7, PC, SC4, BF2, JC4) downriver across both years (2015 and 2016). One example being JC, which had increasing evaporative enrichment from headwaters downriver (JC4 to JC1), however, JC3 (a tributary mouth of the main JC) showed the greatest evaporative enrichment, which could indicate increased lake-to-river connectivity from the southern lakes along that tributary or lower flow leading to increased pooling, which can lead to increased evaporative enrichment, as apposed to the main JC.

Evaporation had a relatively greater influence on OCF during 2015 compared to 2016. Precipitation is likely the main driver for this difference since spring 2015 (May, June) and summer (July, August) precipitation totals (36.2mm, 61.1mm, respectively) are far lower than during 2016 (62.3mm, 96.0mm, respectively).

*Table 2.1. Paired t-test on inter-annual data (July 2015 and July 2016) to highlight statistical difference between sample years. Focusing on deuterium ($\delta^2H$) and $\delta^{18}O$ across all samples, and d-excess for rivers and lakes separately. Statistically significant values are shown in bold (alpha = 0.05).*

| **Paired T-test** | **df** | **p-value** |
|---|---|---|
| Deuterium ($\delta^2H$) (All samples) | 35 | **0.03266** |
| $\delta^{18}O$ (All Samples) | 35 | 0.60044 |
| D-excess (Rivers) | 22 | **0.00034** |
| D-excess (Lakes) | 12 | 0.146968 |

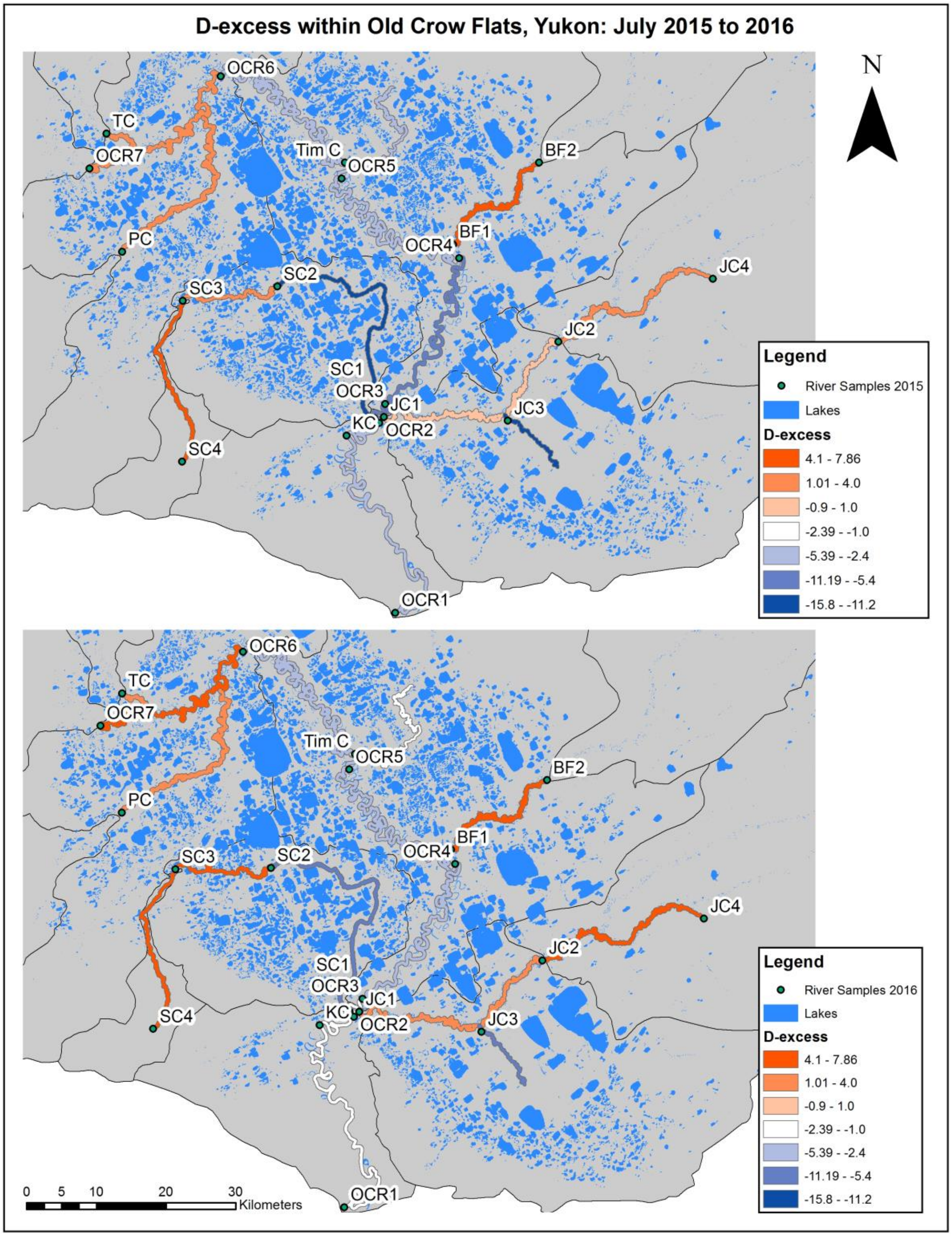



*Figure 2.9. Spatial distribution of d-excess across the OCF drainage network shown with higher concentrations of evaporative enrichment in the darker blue while lower concentrations in lighter blue. *d-excess value from JC3 and TimC have been used to estimate and extend upriver for visual interpretation.*

### 2.4.3 Water Chemistry

Results of the water chemistry data were evaluated using a Principal Component Analysis (PCA) to identify statistical associations among water chemical parameters at each sample site. Each PCA was plotted using the first two principal components as axes, which account for 38% and 22% (July 2015), 41% and 22% (May 2016), 35% and 25% (July 2016) of variability within the data, respectively. PCA was also validated using the scree and broken stick methodologies displayed in Appendix A to verify if PC1 and PC2 accounts for a statistically significant portion of the variability in the data. PCAs from July 2015, May and July 2016 have been built using the same water chemistry variables for each sample period, but scales have been adjusted where necessary to observe patterns among variables.

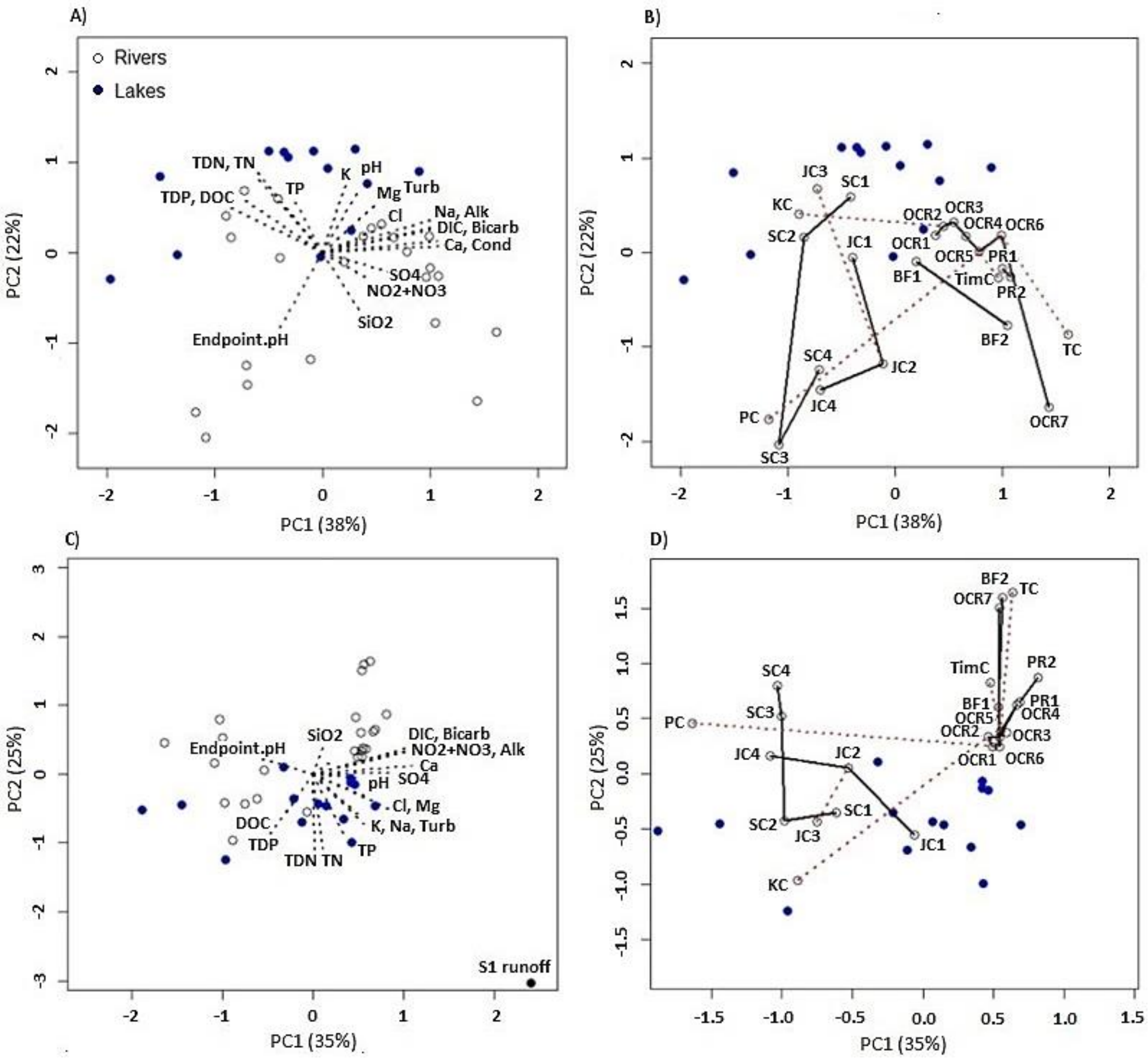



*Figure 2.10. Principal Component Analysis (PCA) showing water chemistry variables as eigenvectors (dotted lines), lake samples as blue circles and river samples as hollow circles. Samples were taken in the field during July (24th-25th) 2015 (A) and July (26th-29th) 2016 (C). River networks were superimposed on the PCAs throughout OCF from July 2015 (B) and July 2016 (D). Each river sampling site is connected by a solid black line whereas tributaries with a single sample are connected by dotted red lines to their main river network. The blue points represent lake samples.*

Water chemistry data shows general variations among lakes and rivers. Most nutrient eigenvectors (TDN, TN, TDP, TP) plot in the upper left quadrant and are negatively correlated with most ions (Mg, Na, $SO_4$, $SiO_2$, K, Ca, Cl; Figure 2.10A). Most lake samples plot closer to nutrient values (especially TN, TDN, TP), pH and K. Some lakes (OCF29, 38) plot between nutrients and ions suggesting a weak correlation with both sets of parameters. Two lakes (OCF26, 55) plot on the far left indicating a strong negative correlation with ions and positive relationship with nutrients. The calculated scores for river sites are much more variable according to the influence of lake water outflow. While most samples are positively correlated with ions, there are some scores plotting relatively close to nutrient eigenvalues and lake values. Hence this plot can be used to identify the relative importance of lake water outflow on river sites.

Connecting river tributary values on the PCA illustrates downstream changes in water chemical properties and identifies the relative importance of inflow from lakes and creeks (Figure 2.10B). Samples from the mouth of those tributaries are the lower numbers (SC1, JC1 etc.) and increasing numbers indicate upstream samples. There is separation along axis 1 between the southern tributaries (JC, SC, KC) and the more northern sites (BF, TimC, TC). SC1 and 2, JC3 and KC are southern OCF sites that plot close to the nutrient eigenvalues and lake scores. BF1 and 2, TC, and TimC are lower-order sites that are correlated with ions in their headwater samples, but plot towards the centre of the PCA, closer to the Old Crow River values. The mouth of tributaries of the main Old Crow River channel (PC, KC) plot close to their neighbouring rivers where PC is near the headwaters of SC (3) and KC near the higher order samples of SC and JC. Finally, the sample from the lowest order portion of the Old Crow River (OCR7) plots close to the other northern headwater tributaries (BF2, TC). As expected, downstream Old Crow River values are influenced by the flow from the PC, TC, TimC, BF, JC, SC, and KC tributaries, which is why downstream Old Crow River values (OCR6-1) plot closer to the centre of the PCA. Finally, the Old Crow River seems to have a slight influence on the Porcupine River (PR), which is also pulled closer to the PCA.

The subset of river samples collected during May ($26^{th}$-$27^{th}$) 2016 was used to identify spring variability in water chemistry across OCF (Figure 2.11A). Samples show less separation among all nutrients and ions. TDP and TP are correlated with DOC towards the bottom right while TDN and TN are split and correlated along with Mg, K, and Cl and indicates greater correlation between major ions and nutrients during the spring season then compared to summer, although these samples represent, almost exclusively, higher-order river sites. Only including higher order sites would alter the PCA results and could be a factor altering the eigenvalues. Water was sampled from a single lake (OCL 1) which had drained partially in 2014 and 2015 into the OCR. It shows a very high correlation with TDN, TN, Mg, K and Cl plotting far from all other river sites. The southern tributaries of JC, SC and KC plot along PC1, away from the other sites and towards the nutrients and DOC indicating a greater influence of lake water outflow. The northern tributaries plot towards the top of the PCA, indicating their inverse relationship with the nutrients and major ions.

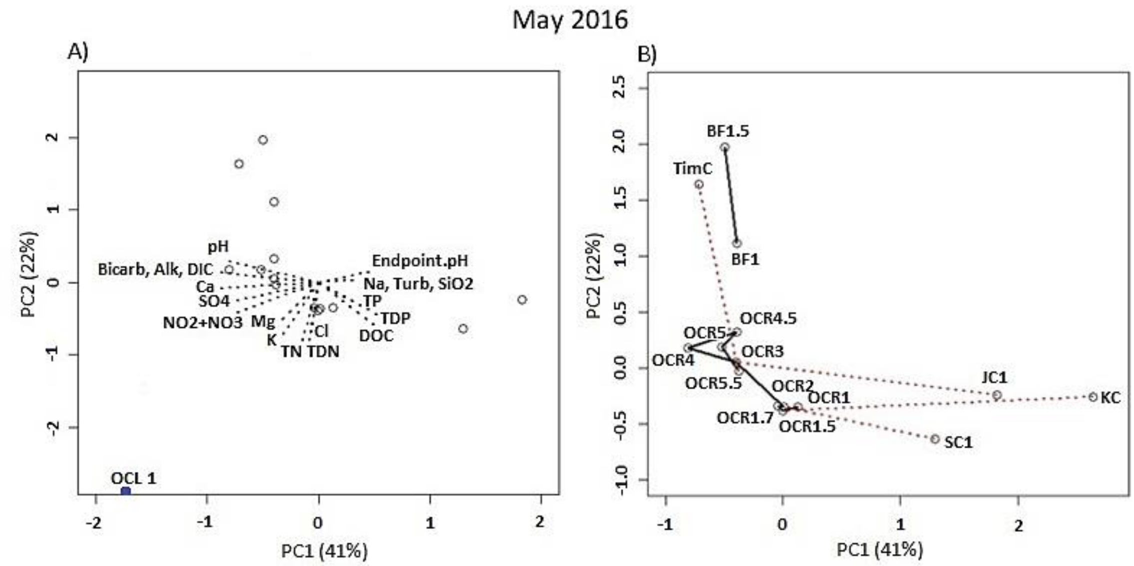



*Figure 2.11. Principal Component Analysis (PCA) showing water chemistry variables as eigenvectors (dotted lines), lake samples as blue circles and river samples as hollow circles. Samples were taken in the field during May (26$^{th}$ - 27$^{th}$) 2016 (A). River networks were superimposed on the PCAs throughout OCF from May 2016 (B). Each river sampling site is connected by a solid black line whereas tributaries with a single sample are connected by dotted red lines to their main river network. Plot B) was focused in on the river networks and the single lake sample (OCL1) falls outside the boundary.*

Samples collected July 26$^{th}$ to 29$^{th}$, 2016 were compared to evaluate inter-annual variation on the hydrology (Figure 2.10C). Sites from July 2015 were resampled along with the addition of an active retrogressive thaw slump sample (S1 runoff), which formed during spring 2016. Results display similarities and differences from 2015 between water chemistry variables and sample sites. The water chemistry variables again show correlations between the major ions (Mg, Na, $SO_4^{2-}$, $SiO_2$, K, Ca, Cl) towards the bottom right, but close to them are the nutrients (TDN, TN, TDP, TP), which are correlated along PC2. Both of these groupings seem to be influenced by a thaw slump, where we obtained a water runoff sample from (S1 runoff). The water chemistry of S1 runoff is highly distinct from the other samples and plots in the bottom right of the PCA. Most of the lake sites are on the bottom portion of the PCA alongside the nutrients and some major ions, but do not have nearly as high concentrations (e.g., in TN) as S1 runoff.

Variability in river water chemistry during 2016 is similar to 2015, with separation between the larger southern tributaries (JC, SC, KC) and northern tributaries (BF, TimC, TC; Figure 2.10D). Similar results show minimal to no inter-annual variability in landscape influence on those river tributaries. There does appear to be variability in the Old Crow River which could be due to a large retrogressive thaw slump during spring 2016, which exported a large amount of debris into the Old Crow River. Its major influence seems to be on carbon and nitrogen export. We also see a shift in the Porcupine River water chemistry from the Old Crow River, but appears to be a more substantial change in 2016 than 2015.

### 2.4.4 Total Suspended Sediments

Samples collected during July 2015, May 2016, and July 2016 from each site were analyzed for total suspended sediments (TSS). Values were plotted with distance from headwater of the Old Crow River to near its mouth (>350 km), which could provide an indication of the influence of lake outflow and erosion have on suspended sediment concentrations across OCF.

Results from the spring (May 2016) show high water and peak sediment export throughout OCF (Figure 2.12). Spring peaks in TSS throughout the Old Crow River (highest= 0.35 g/L) are higher than TSS concentrations during the summer seasons. The Old Crow River generally shows increases downstream until the confluence of Johnson Creek (70 km north of the mouth of the OCR1). There is a relatively abrupt decrease in TSS following inflow from JC1 (0.13 g/L) and SC1 (0.05 g/L). This abrupt decrease is likely due to dilution from the southern tributaries and highlights the strong influence JC and SC have on the Old Crow River.

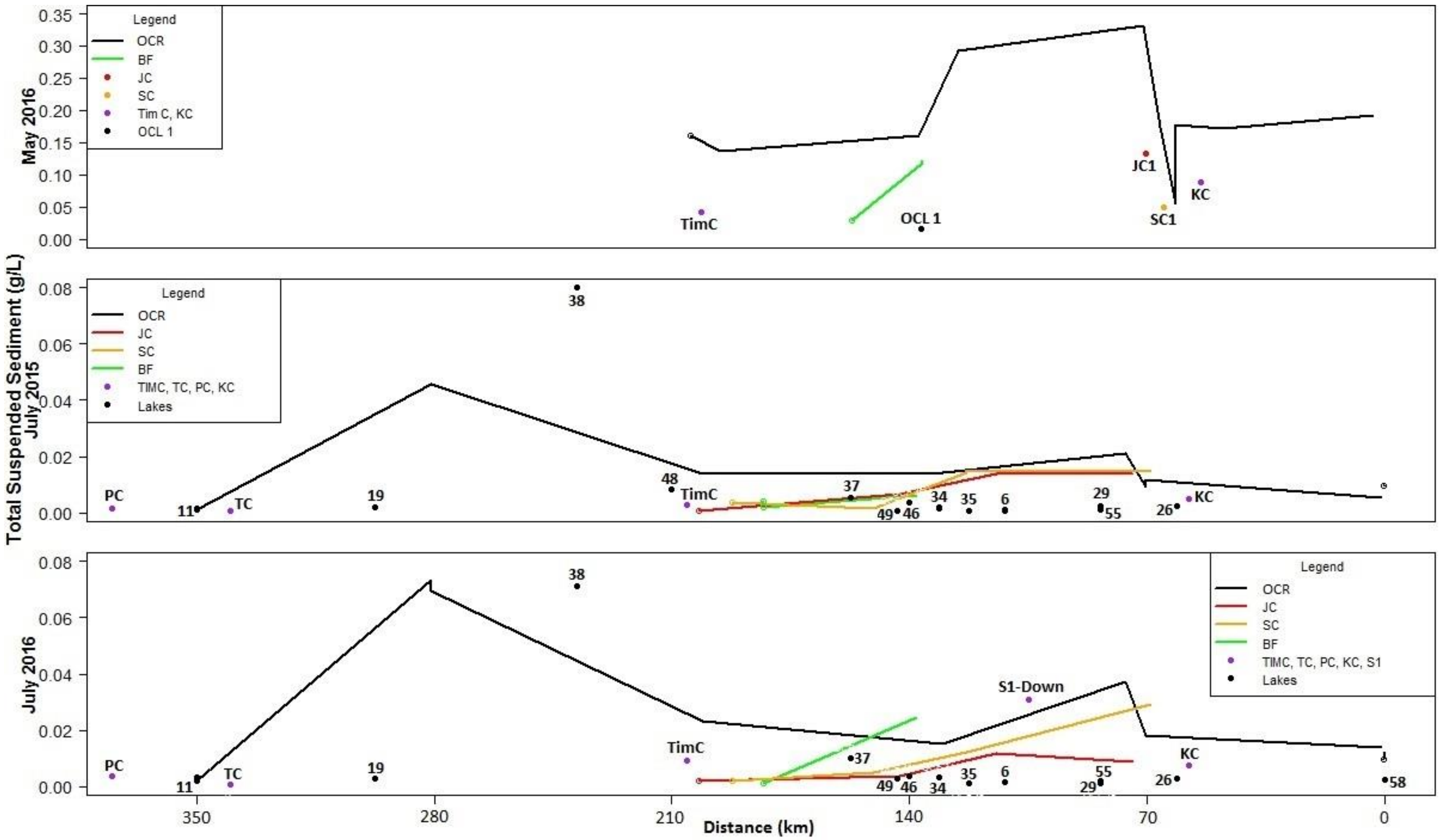



*Figure 2.12. Total suspended sediments calculated from samples collected from July 2015, May 2016 and July 2016 across OCF. River networks have been connected from headwater downriver identifying the influences from each tributary on the OCR hydrology. Lakes have been plotted at their relative distance along the OCR for visual interpretation. *In July 2016, Lake 48 (OCF48) plots above the graph extent (0.176 g/L). ** May 2016 was scaled (y-axis) differently as to retain visible differences from July 2015 and 2016 data.*

Results from July 2015 identify spatial variability in TSS across OCF (Figure 2.12). The highest concentrations of TSS appear to be the along Old Crow River (greatest at 280 km: 0.045 g/L) which shows a general decrease downriver. The highest TSS concentration was in OCF38 (0.08 g/L), a large lake that is often subjected to sediment mixing from high winds. However, lakes overall tend to be lower than rivers in TSS. Other rivers increasing downstream appear to be within the larger southern tributaries JC and SC, which export into the Old Crow River but show only a slight impact where JC connects to the Old Crow River. July 2016 results appear very similar with the highest concentrations of TSS found within the Old Crow River (greatest at 280 km: 0.075 g/L), which also decreases downriver. Lakes OCF38 (0.075 g/L) and OCF48 (0.18 g/L) also contain greater concentrations than all other lakes (Figure 2.12). The southern tributaries again show an increase downriver and only a slight impact on the Old Crow River. Increases in TSS across OCF are likely reflecting the influence of shoreline erosion along the major tributaries whereas lowering values are likely reflective of lake outflow and the settling of sediment.

## 2.5 Discussion

Water isotope signatures can provide key insight of river and creek hydrological characteristics over multiple temporal and seasonal scales. River characteristics during 2015 to 2016 vary spatially and temporally based on a multitude of factors from climatic to local land cover impacts. Previous research has categorized the lake water hydrological conditions (Turner et al., 2010) and identified general drivers of varying river inputs (runoff, snowmelt, rain, and lake water) based on varying isotope signatures (Turner et al., 2014a) across seasonal and annual scales (Balasubramaniam et al., 2015). Our study builds on this work by expanding our spatial range to include lower order river sites and incorporating use of a suite of water chemistry parameters, which provide context of how lake outflow influences downstream river conditions.

Isotope signatures at all tributary samples from July (2015/2016) show increasing evaporative enrichment downriver. This increase indicates greater evaporatively-enriched lake water outflow into nearby rivers. A separation of river water sourcing across OCF can also be seen where northern tributaries (TC, OCR7-5, BF) and headwater sites (SC4, JC4, BF2) had relatively low isotope signatures as compared to higher signatures in downriver sites (SC1, JC1, OCR3-1), approaching lake samples higher along the LEL. During the late summer, there was also direct evaporation of water flowing along the rivers, which could be a small factor, but unlikely accounts for the large shifts in evaporative enrichment.

Seasonal and inter-annual variability in $\delta^2H$, $\delta^{18}O$, and d-excess signatures across OCF have identified variability in lake hydrological conditions (Turner et al., 2014b). The addition of river data highlights our ability to distinguish the strong gradient in river conditions across OCF. Also considering the tendency of lateral thermokarst lake drainage (Mackay, 1988; Hinkel et al., 2007; Marsh et al., 2009) and the indication of an increasing trend over recent decades in OCF (Lantz and Turner, 2015), identifying shifts in lake-to-river connections and drainage events is important in determining climate impact on this sensitive ecosystem. During the early spring season, the isotope compositions of most samples plot close to the average annual isotope composition of precipitation, which indicates mainly snowmelt and direct runoff from precipitation as source water and very minimal evaporative enrichment. However, downstream sites (e.g., BF1, JC1, KC1, KC) have slightly higher isotope values (-175.4 and -22.5 for $\delta^2$H, $\delta^{18}$O, respectively) than upstream (-177.1, -22.8 for $\delta^2$H, $\delta^{18}$O, respectively). These results also show similarities to late summer isotope signatures where southern tributaries (JC, SC, and BF) have the greatest signatures. These similarities indicate an influx of evaporatively enriched lake water present across seasons within those tributaries. This is likely due to direct inflow from nearby lakes along those tributaries, which export water during all ice-free seasons. Inter-annual variability in $\delta^2$H and $\delta^{18}$O is relatively stable with increases across all rivers, and lakes source water remaining stable. The slight overall decrease in evaporative enrichment from July 2015 to 2016 is likely from changes in precipitation, which could have resulted from the very strong El Niño, which began at the end of 2014. The event was considered strong during July 2015, and very strong during the winter of 2015 into spring and summer 2016 (NOAA, 2017), leading to greater precipitation and dilution of evaporatively enriched water.

By expanding on Turner et al. (2014a) to cover all major OCF tributaries, it is evident that the use of isotope signatures and d-excess is capable of characterizing the lake-to-river connectivity, which provides the basis to identify key drivers of downstream changes in water chemistry and sediment load. Lake water chemistry across OCF has been found to be spatially variable and dependent on influences from catchment characteristics (Balasubramaniam et al., 2015). The addition of river water chemistry has identified northern rivers showing strong positive correlation to major ions, whereas southern sites are positively correlated with nutrients. This is likely due to the increased lake-to-river connections in the southern OCF, represented by higher proportions of evaporated water as detected using water isotope tracers ($\delta^{18}$O, $\delta^2$H, and d-excess).

Interestingly, higher lake-river connectivity is spatially-associated with catchments that have undergone increasing growth of shrub vegetation during recent decades (Ahmed and Turner, unpublished data). Additional research should aim to refine our understanding of how shrub vegetation growth and other landscape changes and disturbance (e.g., fire) influence lakes and rivers in OCF.

Seasonal and inter-annual variability on the river hydrology displayed a fairly consistent influence from nutrients across southern tributaries (JC, SC, KC) and from major ions across the north (BF, TC, Tim C, OCR) apart from the retrogressive thaw slump sample (S1-runoff), which was collected during July 2016 and had much higher concentrations of weathering constituents (K, Na, Mg, Cl). These erosional features such as retrogressive thaw slumps and active layer detachment slides have been found to impact local water chemistry (Kokelj et al., 2009a, 2009b; Kokelj and Jorgenson, 2013; Lamhonwah et al., 2017; Lafrenière et al., 2017). The retrogressive thaw slump in OCF appears to be adding high concentrations of nutrient and ions into the Old Crow River from the PCA. Increased runoff from greater precipitation during 2016 may also be why water had higher ions compared to the year prior.

Ongoing landscape change across Arctic permafrost regions must be monitored using techniques that allow us to evaluate spatial correspondence with changes in hydrology and water chemistry. Landscape changes are drivers of spatial variability in river water chemistry, and with continuing climate change, its important we have monitoring programs that can effectively identify shifts in hydrological and limnological conditions. Here, we integrate water chemistry, isotope signatures, and analysis of suspended sediments to effectively detect seasonal and inter-annual patterns in the relative importance of fluvial (erosional) processes and runoff generation processes (e.g., lake drainage and slump runoff) at a broad spatial scale in OCF.

## 2.6 Conclusions

Analyses of chemistry, isotope compositions, and TSS of creek and river water collected from a network of sampling sites across OCF provided key insight of upstream physical processes. Our observations highlight landscape-scale interactions and connections among lakes and rivers in OCF. Water isotope tracers and d-excess results indicate greater connectivity between lakes and rivers across the larger southern tributaries (SC and JC) of OCF as well as BF in the northeast. Chemical influences on the hydrology from surrounding runoff also vary spatially with the southern tributaries showing strong positive correlations with nutrients, whereas the northern tributaries are more positively correlated with major ions. This variability may be in response to differences in land cover from the southern shrub dominated to the northern tundra landscapes and the relative importance of lake water outflow influenced by spatial variability in lake-to-river connections across OCF.

Seasonal fluctuations in water chemistry and isotope signatures are influenced by snowmelt and increased runoff through the system. Lakes and rivers are at their highest water levels during early spring compared to summer water levels, and show less influence from evaporation, which is likely due to the large influx of surface runoff. Signals of lake infiltration are less evident due to lower isotope signatures with less evaporation. Inter-annual variability is due to annual fluctuations in precipitation and lake-to-river connections that alters the evaporative enrichment in the water. Spatial variability in land cover also appears to influence the water chemistry based on runoff from the surrounding landscape.

Strategic sampling across this hydrologically connected drainage network provides the basis to detect disturbance and landscape modifications as climate continues to change. Lateral lake drainage is a regular occurrence across the Arctic (Mackay, 1988; Hinkel et al., 2007; Marsh et al., 2009) and has been detectable using isotope signatures (Turner et al. 2014b) as well as increasing in frequency across OCF (Lantz and Turner, 2015). Thaw features such as retrogressive thaw slumps can also elevate concentrations of solutes and nutrients in local hydrology (Bowden et al., 2008; Kokelj et al., 2009b) facilitating the possibility of identification downriver. Research completed on larger Arctic river systems have studied changing landscape impacts on the hydrology and its affect on the Arctic Ocean (McClelland et al., 2008), however it is also important to identify changes in headwater basins that feed these systems. Continued use of water isotope tracers along with water chemistry analysis from this study could be used as a long-term landscape-monitoring tool across OCF and methods could be adapted for monitoring other lake-rich Arctic permafrost landscapes. The addition of a mixing model approach could also be useful in evaluating the impact of this headwater system on downstream conditions. Work presented here highlights the importance of understanding connections across these Arctic headwater catchments for determining possible long-term alterations as climate continues to change.

Identifying runoff generation processes are important for lake-to-river connections and how increased lake water and erosion will affect downriver habitats. Lake-to-river connections also change water quality and quantity and could affect the drinking water for local community members in Old Crow who rely on the Old Crow River.

## 2.7 References

Balasubramaniam, A.M., Hall, R.I., Wolfe, B.B., Sweetman, J.N., Wang, X., Smith, R., 2015. Source water inputs and catchment characteristics regulate limnological conditions of shallow subarctic lakes (Old Crow Flats, Yukon, Canada). Can. J. Fish. Aquat. Sci. 72, 1058–1072. doi:10.1139/cjfas-2014-0340

Bouchard, F., Turner, K.W., MacDonald, L.A., Deakin, C., White, H., Farquharson, N., Medeiros, A.S., Wolfe, B.B., Hall, R.I., Pienitz, R., Edwards, T.W.D., 2013. Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low. Geophys. Res. Lett. 40, 6112–6117. doi:10.1002/2013GL058635

Bowden, W.B., Gooseff, M.N., Balser, A., Green, A., Peterson, B.J., Bradford, J., 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. J. Geophys. Res. Biogeosciences 113, n/a-n/a. doi:10.1029/2007JG000470

Carroll, M.L., Townshend, J.R.G., DiMiceli, C.M., Loboda, T., Sohlberg, R.A., 2011. Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. Geophys. Res. Lett. 38, n/a-n/a. doi:10.1029/2011GL049427

Coplen, T.B., 1996. New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data. Geochim. Cosmochim. Acta 60, 3359–3360. doi:10.1016/0016-7037(96)00263-3

Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702–1703.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468.

Gonfiantini, R., 1986. Environmental isotopes in lake studies, in: Handbook of Environmental Isotope Geochemistry Edited by P. Fritz and J.C. Fontes. Elsevier, New York, pp. 113–168.

Hinkel, K.M., Jones, B.M., Eisner, W.R., Cuomo, C.J., Beck, R.A., Frohn, R., 2007. Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska. J. Geophys. Res. 112. doi:10.1029/2006JF000584

Hughes, O.L., 1972. Surficial geology of northern Yukon Territory and northwestern district of Mackenzie Northwest Territories (Paper No. 69–36). Geological Survey of Canada.

Jolliffe, I.T., 2002. Principal Component Analysis, Second Edition. ed, Springer series in statistics. Springer.

Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Walter Anthony, K.M., Romanovsky, V.E., 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. J. Geophys. Res. 116. doi:10.1029/2011JG001666

Jorgenson, M.T., Shur, Y.L., Pullman, E.R., 2006. Abrupt increase in permafrost degradation in Arctic Alaska. Geophys. Res. Lett. 33. doi:10.1029/2005GL024960

Kokelj, S.V., Jorgenson, M.T., 2013. Advances in Thermokarst Research: Recent Advances in Research Investigating Thermokarst Processes. Permafr. Periglac. Process. 24, 108–119. doi:10.1002/ppp.1779

Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L., Coutts, R., 2009a. Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada. Permafr. Periglac. Process. 20, 173–184. doi:10.1002/ppp.642

Kokelj, S.V., Zajdlik, B., Thompson, M.S., 2009b. The impacts of thawing permafrost on the chemistry of lakes across the subarctic boreal-tundra transition, Mackenzie Delta region, Canada. Permafr. Periglac. Process. 20, 185–199. doi:10.1002/ppp.641

Labrecque, S., Lacelle, D., Duguay, C.R., Lauriol, B., Hawkings, J., 2009. Contemporary (1951-2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: Remote sensing, numerical modeling, and stable isotope analysis. Arctic 225–238.

Lafrenière, M.J., Louiseize, N.L., Lamoureux, S.F., 2017. Active layer slope disturbances affect seasonality and composition of dissolved nitrogen export from High Arctic headwater catchments. Arct. Sci. 3, 429–450. doi:10.1139/as-2015-0009

Lamhonwah, D., Lafrenière, M.J., Lamoureux, S.F., Wolfe, B.B., 2017. Multi-year impacts of permafrost disturbance and thermal perturbation on High Arctic stream chemistry. Arct. Sci. 3, 254–276. doi:10.1139/as-2016-0024

Lantz, T.C., Turner, K.W., 2015. Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. J. Geophys. Res. Biogeosciences 120, 513–524. doi:10.1002/2014JG002744

Lauriol, B., Duguay, C.R., Riel, A., 2002. Response of the Porcupine and Old Crow rivers in northern Yukon, Canada, to Holocene climatic change. The Holocene 12, 27–34. doi:10.1191/0959683602hl517rp

MacDonald, L.A., Turner, K.W., Balasubramaniam, A.M., Wolfe, B.B., Hall, R.I., Sweetman, J.N., 2012. Tracking hydrological responses of a thermokarst lake in the Old Crow Flats (Yukon Territory, Canada) to recent climate variability using aerial photographs and paleolimnological methods. Hydrol. Process. 26, 117–129. doi:10.1002/hyp.8116

Mackay, J.R., 1988. Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie. Geol. Surv. Can. 88–1D, 83–90.

Manasypov, R.M., Pokrovsky, O.S., Kirpotin, S.N., Shirokova, L.S., 2014. Thermokarst lake waters across the permafrost zones of western Siberia. The Cryosphere 8, 1177–1193. doi:10.5194/tc-8-1177-2014

Marsh, P., Neumann, N.N., 2001. Processes controlling the rapid drainage of two ice-rich permafrost-dammed lakes in NW Canada. Hydrol. Process. 15, 3433–3446. doi:10.1002/hyp.1035

Marsh, P., Russell, M., Pohl, S., Haywood, H., Onclin, C., 2009. Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000. Hydrol. Process. 23, 145–158. doi:10.1002/hyp.7179

McClelland, J.W., Holmes, R.M., Peterson, B.J., Rainer, A., et al., 2008. Development of a Pan-Arctic Database for River Chemistry. EOS Trans. Am. Geophys. UNION 89, 217–224.

Morlan, R.., 1980. Taphonomy and archaeology in the Upper Pleistocene of the northern Yukon Territory: a glimpse of the peopling of the New World, Mercury series /

National Museum of Man Paper / Archaeological Survey of Canada; no. 94 Mercury series.
Morlan, R.E., 2003. Current perspectives on the Pleistocene archaeology of eastern Beringia. Quat. Res. 60, 123–132. doi:10.1016/S0033-5894(03)00070-X
NOAA, 2017. Historical El Nino/ La Nina episodes (1950-present) [WWW Document]. Natl. Weather Serv. Clim. Predict. Cent. URL http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml
Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2018. Package "vegan." Community ecology package, version 2.
Porter, T.J., Pisaric, M.F.J., 2011. Temperature-growth divergence in white spruce forests of Old Crow Flats, Yukon Territory, and adjacent regions of northwestern North America. Glob. Change Biol. 17, 3418–3430. doi:10.1111/j.1365-2486.2011.02507.x
Rampton, V.N., 1988. Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories, Memoir / Geological Survey of Canada. Energy, Mines and Resources Canada; Canadian Gov't Pub. Centre, Supply and Services Canada [distributor], Canada: Ottawa, Canada.
Riordan, B., Verbyla, D., McGuire, A.D., 2006. Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. J. Geophys. Res. Biogeosciences 111. doi:10.1029/2005JG000150
Smith, L.C., Sheng, Y., MacDonald, G.M., Hinzman, L.D., 2005. Disappearing Arctic Lakes. Science 308, 1429.
Tondu, J.M.E., Turner, K.W., Wolfe, B.B., Hall, R.I., Edwards, T.W.D., McDonald, I., 2013. Using Water Isotope Tracers to Develop the Hydrological Component of a Long-Term Aquatic Ecosystem Monitoring Program for a Northern Lake-Rich Landscape. Arct. Antarct. Alp. Res. 45, 594–614. doi:10.1657/1938-4246-45.4.594
Toniolo, H., Kodial, P., Hinzman, L.D., Yoshikawa, K., 2009. Spatio-temporal evolution of a thermokarst in Interior Alaska. Cold Reg. Sci. Technol. 56, 39–49. doi:10.1016/j.coldregions.2008.09.007
Turner, K.W., Edwards, T.W.D., Wolfe, B.B., 2014a. Characterising Runoff Generation Processes in a Lake-Rich Thermokarst Landscape (Old Crow Flats, Yukon, Canada) using $\delta^{18}O$, $\delta^{2}H$ and d-excess Measurements: Characterising Runoff with Water Isotope Tracers in Old Crow Flats, Yukon. Permafr. Periglac. Process. 25, 53–59. doi:10.1002/ppp.1802
Turner, K.W., Wolfe, B.B., Edwards, T.W.D., 2010. Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. J. Hydrol. 386, 103–117. doi:10.1016/j.jhydrol.2010.03.012
Turner, K.W., Wolfe, B.B., Edwards, T.W.D., Lantz, T.C., Hall, R.I., Larocque, G., 2014b. Controls on water balance of shallow thermokarst lakes and their relations with catchment characteristics: a multi-year, landscape-scale assessment based on water isotope tracers and remote sensing in Old Crow Flats, Yukon (Canada). Glob. Change Biol. 20, 1585–1603. doi:10.1111/gcb.12465

Walvoord, M.A., Striegl, R.G., 2007. Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen. Geophys. Res. Lett. 34. doi:10.1029/2007GL030216

Wolfe, B.B., Humphries, M.M., Pisaric, M.F., Balasubramaniam, A.M., Burn, C.R., Chan, L., Cooley, D., Froese, D.G., Graupe, S., Hall, R.I., others, 2011. Environmental change and traditional use of the Old Crow Flats in northern Canada: an IPY opportunity to meet the challenges of the new northern research paradigm. Arctic 64, 127.

Wolfe, B.B., Turner, K.W., 2008. Near-record precipitation causes rapid drainage of Zelma Lake, Old Crow Flats, northern Yukon Territory. Meridian Spring Edition, 7–12.

Yoshikawa, K., Hinzman, L.D., 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near council, Alaska. Permafr. Periglac. Process. 14, 151–160. doi:10.1002/ppp.451

Zazula, G.D., Duk-Rodkin, A., Schweger, C.E., Morlan, R.E., 2004. Late Pleistocene chronology of Glacial Lake Old Crow and the north-west margin of the Laurentide ice sheet, in: Quaternary Glaciations-Extent and Chronology Part II: North America. Elsevier London, pp. 347–362.

Chapter 3: Intended for publication in the Journal of Hydrology

# Spatial variability in dissolved inorganic and organic carbon export through a lake-rich permafrost landscape, Old Crow Flats, Yukon.

D. Hughes[1], K.W. Turner[2]

[1]Department of Earth Science, Brock University, St. Catharines, Ontario, Canada, [2]Department of Geography and Tourism Studies, Brock University, St. Catharines, Ontario, Canada

## 3.1 Introduction

Arctic permafrost landscapes are prevalent in North America and Eurasia (Brown et al., 1997, 2002) and are highly sensitive to changes in climate, such as the pronounced increase in Arctic temperatures over the last 30 years (IPCC, 2013). Lake and ice-rich permafrost landscapes are particularly dynamic as surface water can produce positive feedbacks (erosional and thermal) that amplify permafrost degradation (Jorgenson et al., 2001; Toniolo et al., 2009). Landscape changes responding to climate have included variability in thermokarst lake area (Smith et al., 2005; Riordan et al., 2006; Jones et al., 2011) along with erosional features such as expansion of channel networks (Toniolo et al., 2009), increased river bank erosion (Costard et al., 2007), increasing rates of retrogressive thaw slumps (Lantz and Kokelj, 2008), and active layer detachment slides (Lamoureux et al., 2014; Lamhonwah et al., 2017; Lafrenière et al., 2017). These landscape changes can also impact the hydrology, water chemistry and sediment loading of downstream drainage systems. The sudden export of lake water (Turner et al., 2014a) or exposure of previously frozen soils (Lamoureux et al., 2014; Lamhonwah et al., 2017) have been shown to alter hydrologic conditions. With over 50% of the terrestrial organic carbon pool likely locked in permafrost landscapes (Tarnocai et al., 2009; Hugelius et al., 2014), there are concerns that increasing permafrost degradation could mobilize carbon towards downstream environments and possibly enhance greenhouse gas ($CO_2$ and $CH_4$) concentrations (Spencer et al., 2015; Schuur et al., 2015). Here we assess carbon concentration spatial patterns and sources across the drainage system of Old Crow Flats, Yukon.

### 3.1.1 Carbon Processes in Arctic Environments

Amount of carbon export from permafrost along hydrologic pathways is directly related to catchment characteristics and the sediment characteristics of the thawed permafrost. Carbon in the form of organic material can decompose after thaw and be released directly as $CO_2$, which could enter the atmosphere, or become trapped within the soil pore space. Dissolved organic carbon (DOC) can be carried within groundwater flow into the nearest hydrologic surface network, where it can mineralize and release $CO_2$ (Cole et al., 2007). The biodegradability of DOC from permafrost thaw and collapse has been found in some areas to be very high (Abbott et al., 2014; Spencer et al., 2015), which allows for accelerated C transfer to the atmosphere. Dissolved Inorganic Carbon (DIC) in riverine systems is a measure of carbonate, bicarbonate, carbonic acid, and carbon dioxide concentrations. Specifically, bicarbonate and carbonate (which is minimal at pH <9) can become liberated from the permafrost via chemical weathering. This process uses $CO_2$ and is considered a carbon sink for its specific residence time (~ $10^4$ years; Berner and Berner, 2012). These processes create a form of balance between $CO_2$ release and sequestration depending on the concentrations of DOC and DIC from their weathering constituents (see Lerman et al., 2007). Identifying DIC export in addition to DOC export along hydrological pathways enhances our knowledge of the local carbon balance. Carbon sourcing may also be studied using isotope signatures $\delta^{13}C$ for DIC and DOC within the local hydrologic system. The $\delta^{13}C$ for DOC in river water has been used to differentiate landscape inputs between C3, C4 and CAM vegetation (O'Leary, 1988) along with identifying $\delta^{13}C$ depleted by methane oxidation (Hindshaw et al., 2016). $\delta^{13}C$ for DIC in river water systems is mainly from the dissolution of $CO_2$ within the soil, weathering of carbonate rocks and exchange with atmospheric $CO_2$ (Yang et al., 1996).

Recent large projects to study Arctic hydrology and carbon have been the PARTNERS project (Pan-Arctic Transport of Nutrients, Organic Matter and Suspended Sediments), which began in 2002 and ran until 2007. Its focus was on the six major circumpolar rivers (the Ob', Yenisei, Kolyma, Yukon and Mackenzie rivers) measuring their biogeochemistry across their annual hydrologic cycles. These six river catchments have a total area of $10.9 * 10^6$ $km^2$ (Holmes et al., 2012) and contain more than 50% of the freshwater flux into the Arctic Ocean. This project has since been followed up with the Arctic Great Rivers Observatory, which began in 2009 and continues today using identical sites and protocols. These projects have provided improved annual and seasonal estimates of DOC, inorganic and organic nutrients, along with flow weighted mean estimates of alkalinity (Cooper et al., 2008; Holmes et al., 2012). Studies on carbon export in Arctic aquatic environments use higher resolution data to study DIC and/or DOC flux across the six major circumpolar rivers (Tank et al., 2012a, 2012b). Tank et al. (2012a) found that increases in DIC flux from runoff and permafrost thaw (containing high carbonate concentrations) increased carbon sequestration, while DOC flux was more region specific based on organic carbon concentrations. This indicates that with permafrost thaw, increases in DIC should counteract and balance part of the organic carbon mineralization and $CO_2$ release through sequestration. Hence, DIC sequestration plays an important role in the carbon budget, but is dependant on the organic carbon concentrations within the permafrost for each specific area.

Studies have also used $\delta^{13}C$ for both DIC and DOC to gain a better understanding of the carbon cycle dynamics and source material for specific study sites (Wang et al., 1998; Li et al., 2010; Hindshaw et al., 2016). Li et al. (2010) utilized DIC concentrations along with $\delta^{13}C$ DIC to interpret carbon sourcing in a karst rich environment in the Changjiang River Basin, China and found the major sources to be from carbonate weathering and $CO_2$ derived from the soil. They also found seasonal variability in the carbon pool from spring melt, to summer, and winter, which has also been widely documented in organic carbon studies (Raymond et al., 2007; Spencer et al., 2008; Wickland et al., 2012). Hindshaw et al. (2016) discuss $\delta^{13}C$ DOC values as they pertain to the stream water chemistry and microbial communities in high Arctic catchments. Hindshaw et al. (2016) found that smaller streams had greater concentrations of $\delta^{13}C$ DOC from methane cycling, while larger rivers were dominated by runoff from catchments covered in C3 plants and soil organic matter.

### 3.1.2 Previous research in OCF

Old Crow Flats (OCF) is an Arctic permafrost landscape that is internationally regarded for its ecological and cultural integrity owing to the ~8500 waterbodies that span the 5600-km$^2$ area. Recent research in OCF has focussed on identifying spatial patterns in lake and river hydrological conditions and associated drivers (Turner et al., 2010, 2014b, 2014a; Lantz and Turner, 2015). Studies have highlighted the spatial variability in catchment characteristics and runoff generation processes that influence the local hydrology (Turner et al., 2014a, 2014b), as well as landscape changes such as increase frequency in lake drainage events (Lantz and Turner, 2015). These changes could also alter the carbon export and biodegradability from permafrost landscapes (Abbott et al., 2014; Spencer et al., 2015), however, the spatial variability in carbon export and mobility in OCF remains unknown. Further, understanding the influence of climate induced landscape changes (e.g. retrogressive thaw slumps) on the export of carbon is needed to predict future impacts on downriver basins and the atmospheric carbon balance. Spatial variability in landcover (vegetation, sediments, lakes) and seasonal and inter-annual fluctuations in temperature and precipitation are expected to influence carbon export to the hydrologic system. Landscape changes are also hypothesised to impact carbon export as well as impacting downriver water chemistry. Here, we use carbon concentrations and isotope signatures to capture spatial variability in carbon export across OCF, identify the impact of a retrogressive thaw slump event on the carbon budget, and the possible influences on the downstream carbon concentrations. This research provides insight of the spatial variability in local carbon export across OCF and provides a baseline for future investigations of the impacts of intensifying climate-induced landscape changes that may alter the carbon budget.

## 3.2 Study Site

Old Crow Flats (OCF) is a lake-rich thermokarst landscape located in northern Yukon, Canada. This 5600-km$^2$ wetland complex is the traditional territory of the Vuntut Gwitchin First Nations (VGFN) who mostly reside in the town of Old Crow 45 km south of central OCF. OCF is recognized by the Ramsar Convention as a wetland of international importance (1982) and is a crucial habitat for local wildlife, while also providing resources for the local community. OCF occupies the former basin of glacial lake Old Crow, which was a periglacial feature west of the Laurentide Ice Sheet (LIS) during the early Wisconsinan (Zazula et al., 2004). The area drained leaving behind silt and clay rich sediments as well as prehistoric animal remains (Morlan, 2003).

Today, OCF is estimated to contain over 8700 thermokarst lakes and ponds (Lantz and Turner, 2015) which vary in depth (0.5-6m) and area (1-3700 ha) (Labrecque et al., 2009). The area also has a dense river network with the Old Crow River and its major river tributaries incised in periglacial sediments of former glacial lake Old Crow (Morlan, 1980; Lauriol et al., 2002). Many lakes have direct connection channels, usually between nearby lakes or main river channels, while others are considered closed-basin. The area also is estimated to contain little groundwater flow due to the low hydraulic conductivity of the continuous permafrost (Hughes, 1972). The main water export path out of the flats is the Old Crow River and its major tributaries, which has large meanders and have formed many full and drained oxbow lakes as well as previous river channel scars. The Old Crow River connects to the Porcupine River north of Old Crow, and continues towards Alaska via the Yukon River.

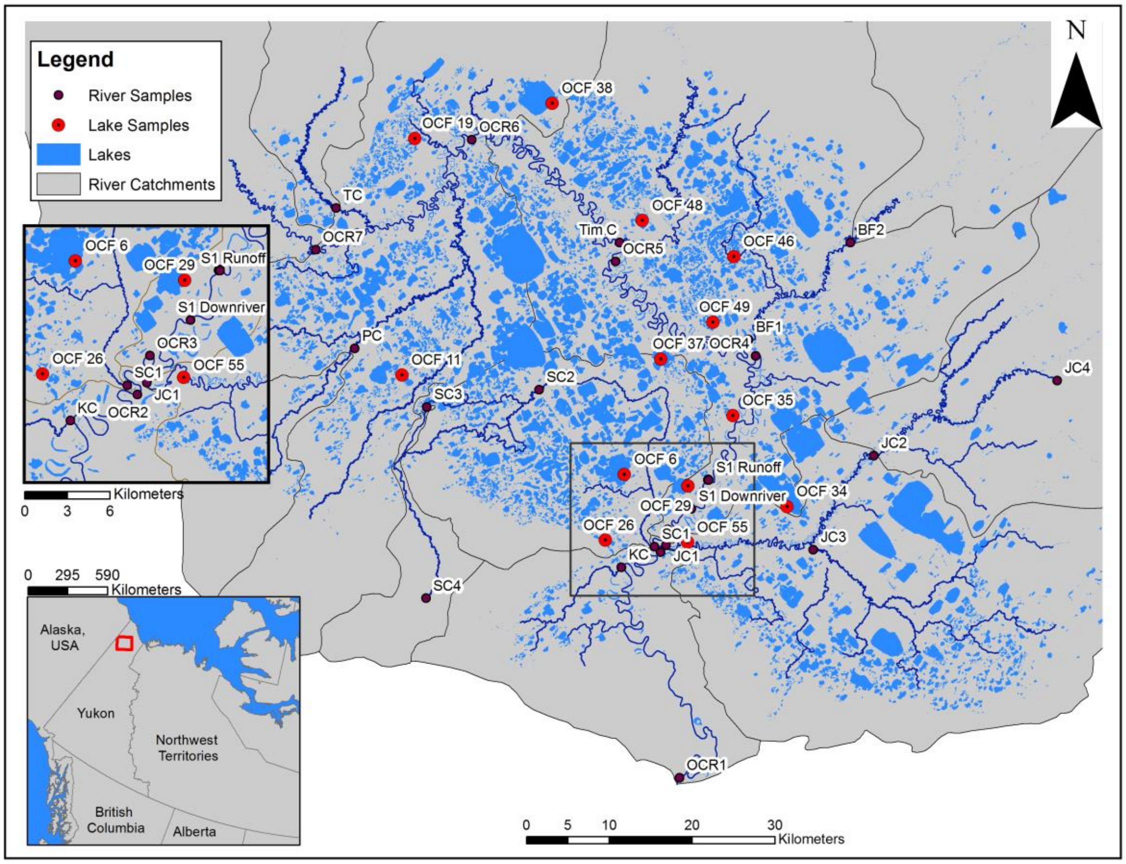



*Figure 3.1. River and lake sample sites collected across Old Crow Flats over July 2015 and 2016, along with a subset taken during May 2016.*

## 3.3 Methods

### 3.3.1 Sample Collection and Analysis

Water samples collected throughout the OCF drainage system was used to identify spatial patterns in carbon export on inter-annual and seasonal scales. Samples were collected in 4 L carboys and 1 L high-density polyethylene environmental sample bottles during July 2015 and 2016 ($24^{th}$-$25^{th}$ and $26^{th}$-$29^{th}$, respectively) using a helicopter, and a smaller number of samples (15 river and 1 lake) were obtained during May 2016 ($26^{th}$-$27^{th}$) when water levels were high enough to access sites by boat. All collection containers were thoroughly rinsed three times with river/lake water at each site before collecting the water sample. River sites were collected along ~350 km of the Old

Crow River and its major tributaries (Figure 3.1). Locations were selected for the purpose of tracking downstream transitions in carbon and are reflected in the river site naming acronyms. River site numbers represent their order upstream (e.g. river numbering is from highest upriver to lowest downriver: e.g. OCR7 – OCR1). Water was also sampled at 13 lake sites, which have been monitored in collaboration with Parks Canada since 2007 (Tondu et al., 2013).

Water samples were stored in a fridge at 4$^{o}$C and pre-processed in Old Crow prior to being sent to the laboratory for processing. Samples were processed for a suite of water chemistry parameters including total nitrogen (TN), total phosphorus (TP), pH, turbidity (Turb), conductivity, alkalinity (Alk) and total gran alkalinity were only pre-screened through a 200 µm mesh to remove any large particles. Major ions (Mg, Na, $SO_4$, $SiO_2$, K, Ca, Cl), nitrates ($NO_2^-$ + $NO_3^-$), total dissolved phosphorus (TDP), total dissolved nitrogen (TDN), dissolved inorganic and organic carbon (DIC/DOC) were pre-screened through a 200 µm mesh and filtered through 0.45 µm acetate filters. Sample analysis was completed at the Biogeochemical Analytical Service Laboratory (BASL) located at the University of Alberta.

Samples were also pre-processed for $\delta^{13}$C DIC and DIC by filtering through a 200 µm mesh and through 0.45 µm acetate filters. The samples were sent to the G.G. Hatch Stable Isotope Laboratory at the University of Ottawa for processing using standard methods (St-Jean, 2003; OI Analytical, 2005). The samples were run on an Aurora Model 1030W TOC Analyser and interfaced to an isotope ratio mass spectrometer. Isotope concentrations are expressed as δ values, which represent per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard, with a precision of ±0.40‰.

Correlations among water chemistry parameters were analyzed using a Principal Component Analysis (PCA). A PCA reduces the dimensionality of the data while retaining as much of the variation as possible. The first few principal components retain the highest amount of variation and are used to replot the data. The PCA was created using the vegan library (version 2.4-3; Oksanen et al., 2017) in Rstudio and running an unconstrained Redundancy Analysis (RDA). The resulting principal component axes are validated with the use of a scree plot, which displays the variance of each principal component. The broken stick methodology is used, which represents a random (null) model and calculates a set of expected values; principal components that fall above the null model are retained (Appendix A).

### 3.3.2 Retrogressive Thaw Slump

During the 2016 summer season, an active retrogressive thaw slump exported a large amount of surficial debris into the Old Crow River between May 26$^{th}$ and July 26$^{th}$. The slump was not observed during the May boat trip, but locals saw the exported sediment blocking the majority of the Old Crow River within this time frame prior to our July sampling. The volume of material ejected during the initial slump (~29,000 $m^3$) was calculated ~1 month after initiation of the retrogressive thaw slump using an unmanned aerial vehicle (UAV) survey (144 UAV images). The images were orthorectified using handheld GPS coordinates collected in the field, georeferenced and modeled to calculate the estimated volume using Pix4D software (Figure 3.2). Direct runoff from the retrogressive thaw slump was also sampled and analyzed for a suite of water chemistry parameters including Dissolved Inorganic and Organic Carbon (DIC/DOC) concentrations and isotope signatures ($\delta^{13}C$).

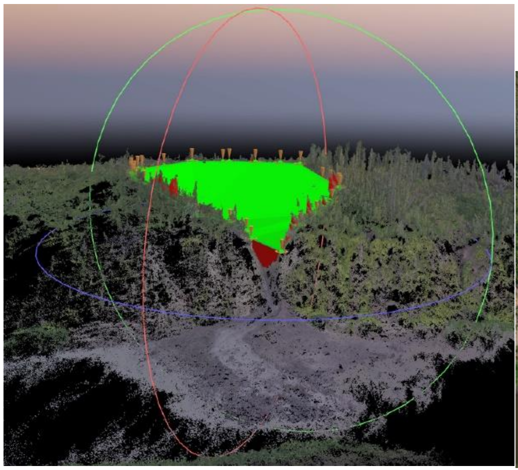


*Figure 3.2. Retrogressive thaw slump digitally modeled using Pix4D software (left) and an image taken from a helicopter which shows the extent of debris exported into the Old Crow River (right). Photos by: Dr. Kevin Turner*

## 3.4 Results

### 3.4.1 Spatial variability in carbon

DIC and DOC concentrations (ppm) show an inverse relationship moving downstream along the Old Crow River during July 2015 and 2016 (Figure 3.3 and 3.4). DIC concentrations are highest at headwater sites (OCR7, TC, BF2; >30ppm), and decrease downriver. The larger southern tributaries (JC and SC) had the lowest DIC concentrations (<8ppm). DOC concentrations are lowest at headwater sites (<8ppm) and increase downriver. The southern tributaries had the highest DOC concentrations (>10ppm). DIC mean concentrations were greater during July 2015 than 2016 (20.0ppm compared to 16.2ppm), whereas mean DOC concentrations were greater in 2016 (9.8ppm compared to 11.6ppm), which could be linked to annual and inter-annual variability in precipitation and temperature altering lake-to-river connections and runoff.

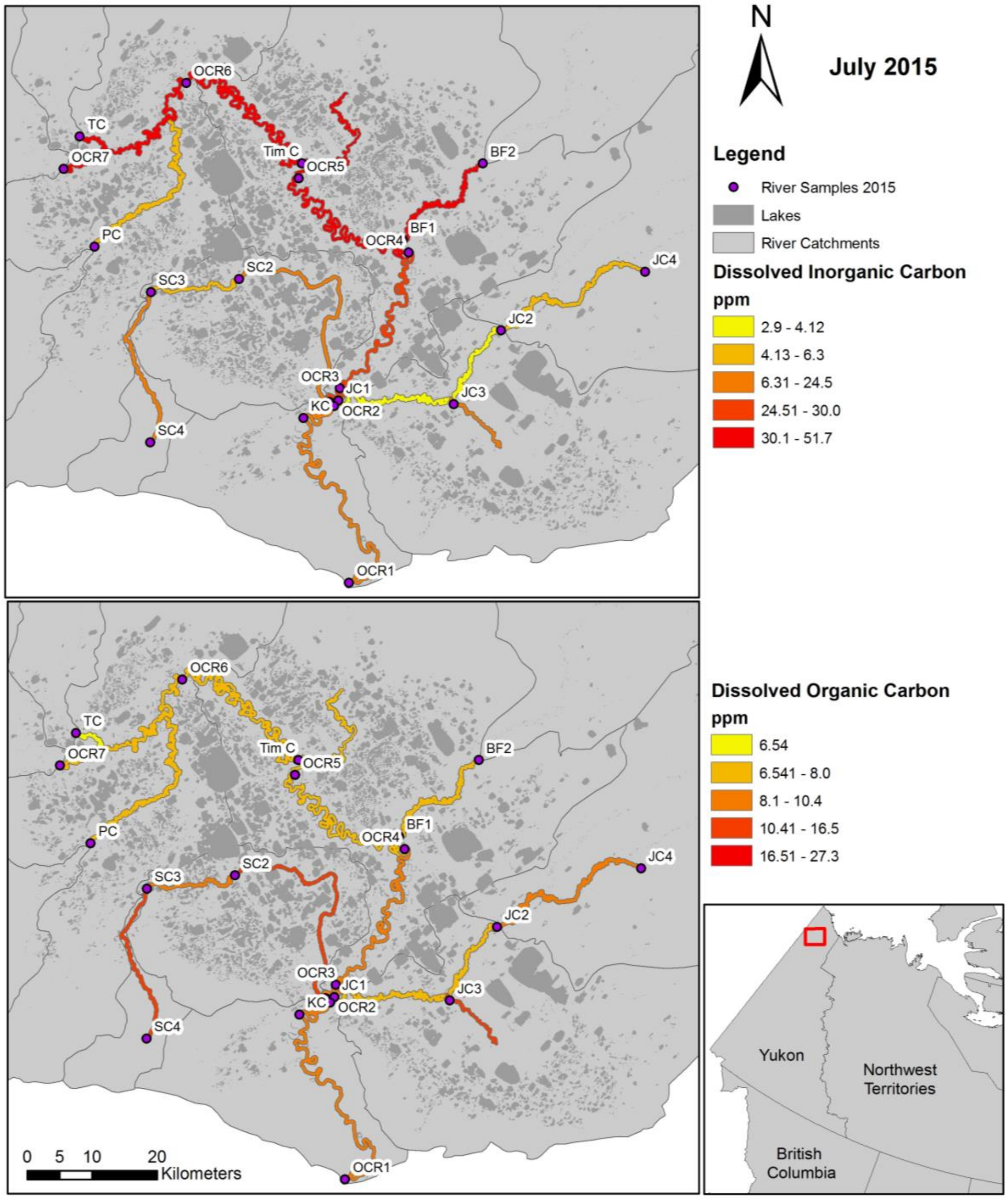



*Figure 3.3. Dissolved inorganic and organic concentrations (ppm) and movement throughout OCF and the major river networks during July 2015.*

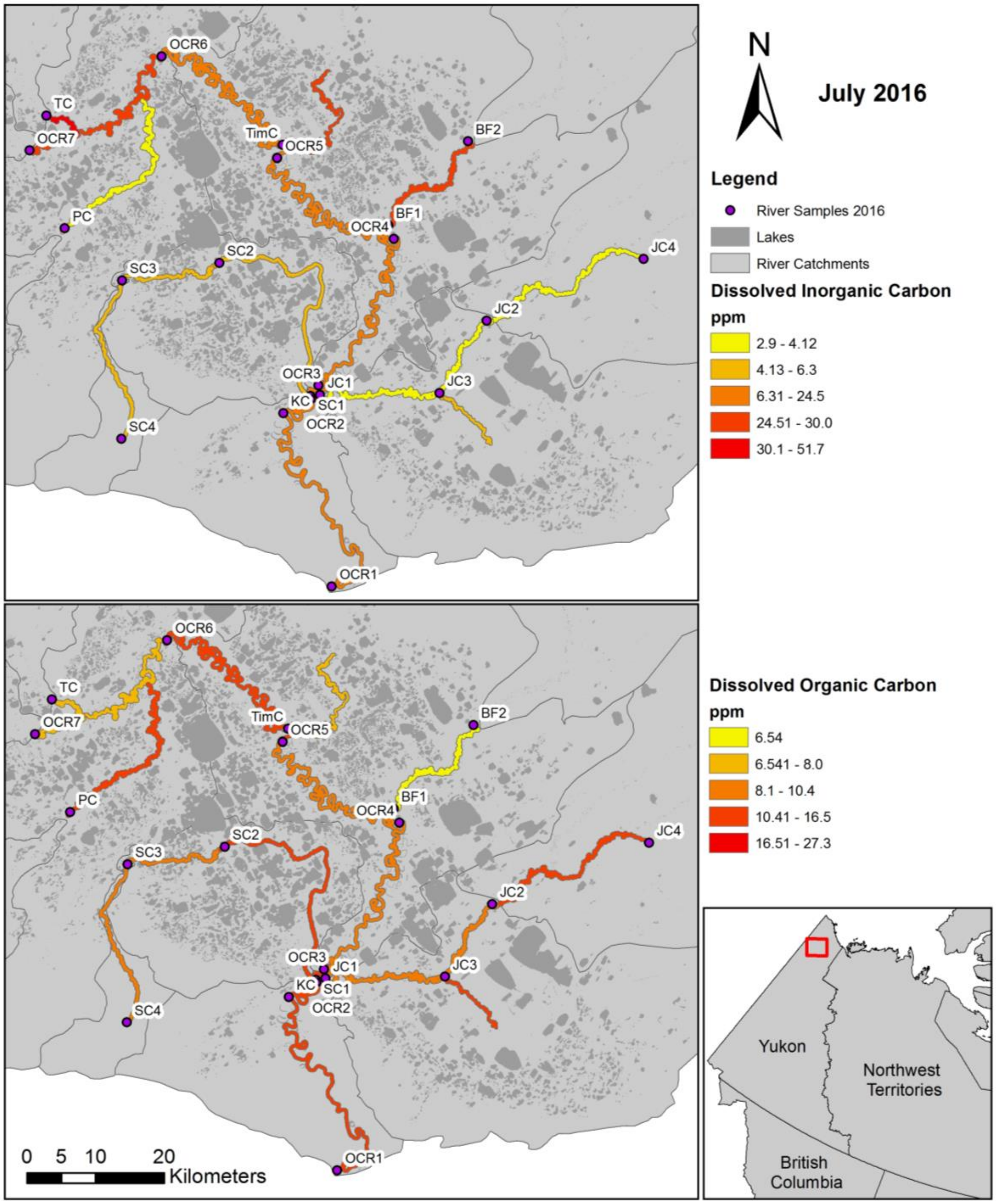



*Figure 3.4. Dissolved inorganic and organic concentrations (ppm) and movement throughout OCF and the major river networks during July 2016.*

Carbon 13 isotopic signatures ($\delta^{13}C$) from July 2015 (Figure 3.5) between DIC and DOC are similar. The Old Crow River appears to have the highest isotopic signature (>-9‰, >-25‰; for DIC and DOC, respectively), which could be from increased lake water, and riverbank erosion. DIC increases from headwater sampling sites downriver, whereas DOC is generally decreasing. The southern tributaries (JC, SC) have the lowest signatures for both DIC and DOC (<-12‰, <-27‰; respectively), which decrease the isotope signature along the southern reach of the Old Crow River downstream from their confluences. DIC samples from July 2016 (Figure 3.6) display a similar spatial pattern as 2015 with increasing values downstream. The isotope signature for DOC shows the opposite pattern during 2015 with downstream increases in $\delta^{13}$C DOC.

Changes in temperature and precipitation could also impact the carbon mobility and export across OCF. Increases in precipitation from 2015 to 2016 as well as temperature changes (mainly during the winter) could alter DIC and DOC availability and mobility across the two sample years (Figure 2.3, 2.4). Also, the addition of debris from the active retrogressive thaw slump along the Old Crow River could impact DIC and DOC concentrations and isotopic signatures. Analyzing these results along the Old Crow River and its major tributaries, with respect to downriver change could also highlight the impact of the retrogressive thaw slump on lateral carbon export.

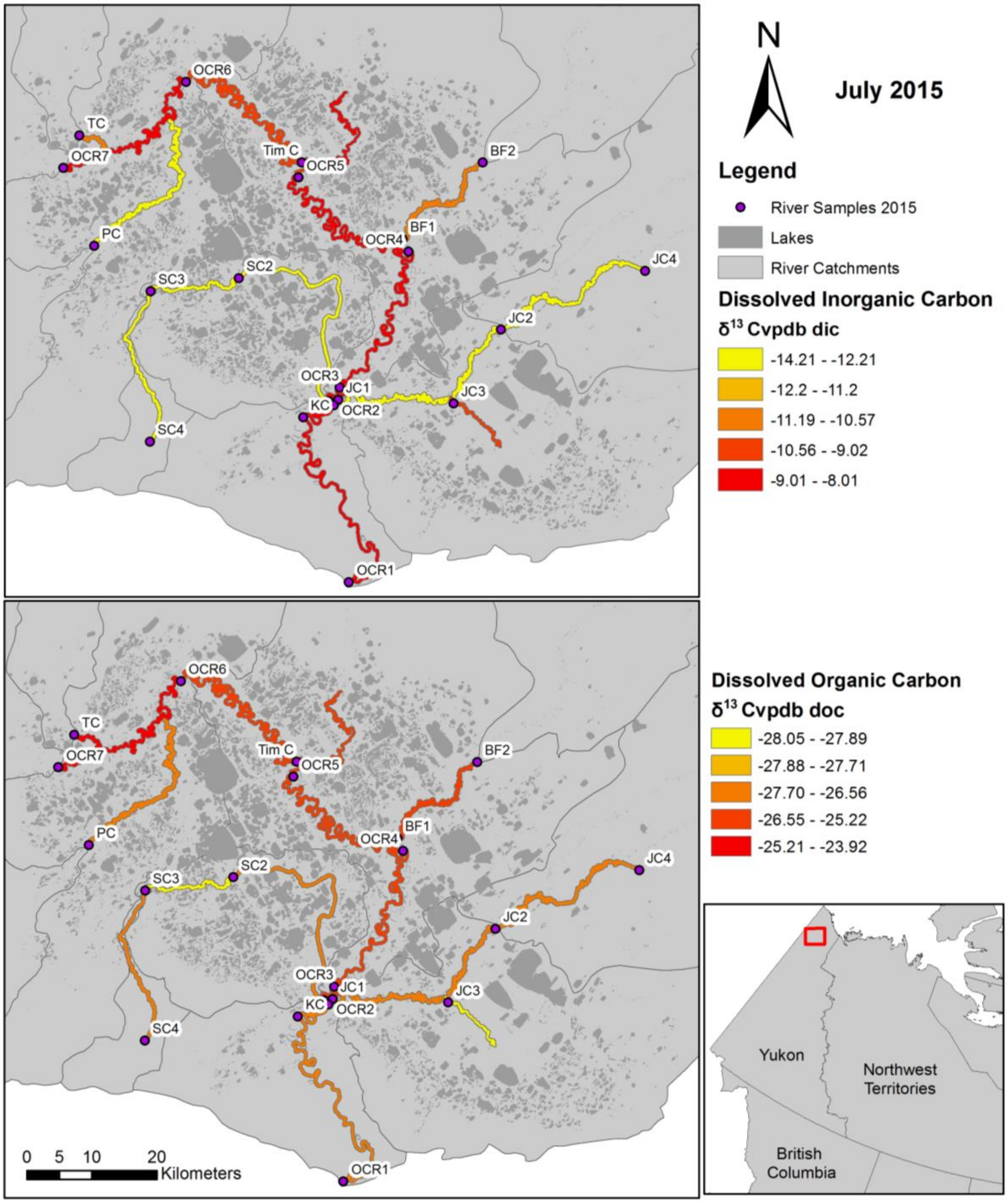



*Figure 3.5. Dissolved inorganic and organic isotope signatures ($\delta^{13}C$) and movement throughout OCF and the major river networks during July 2015.*

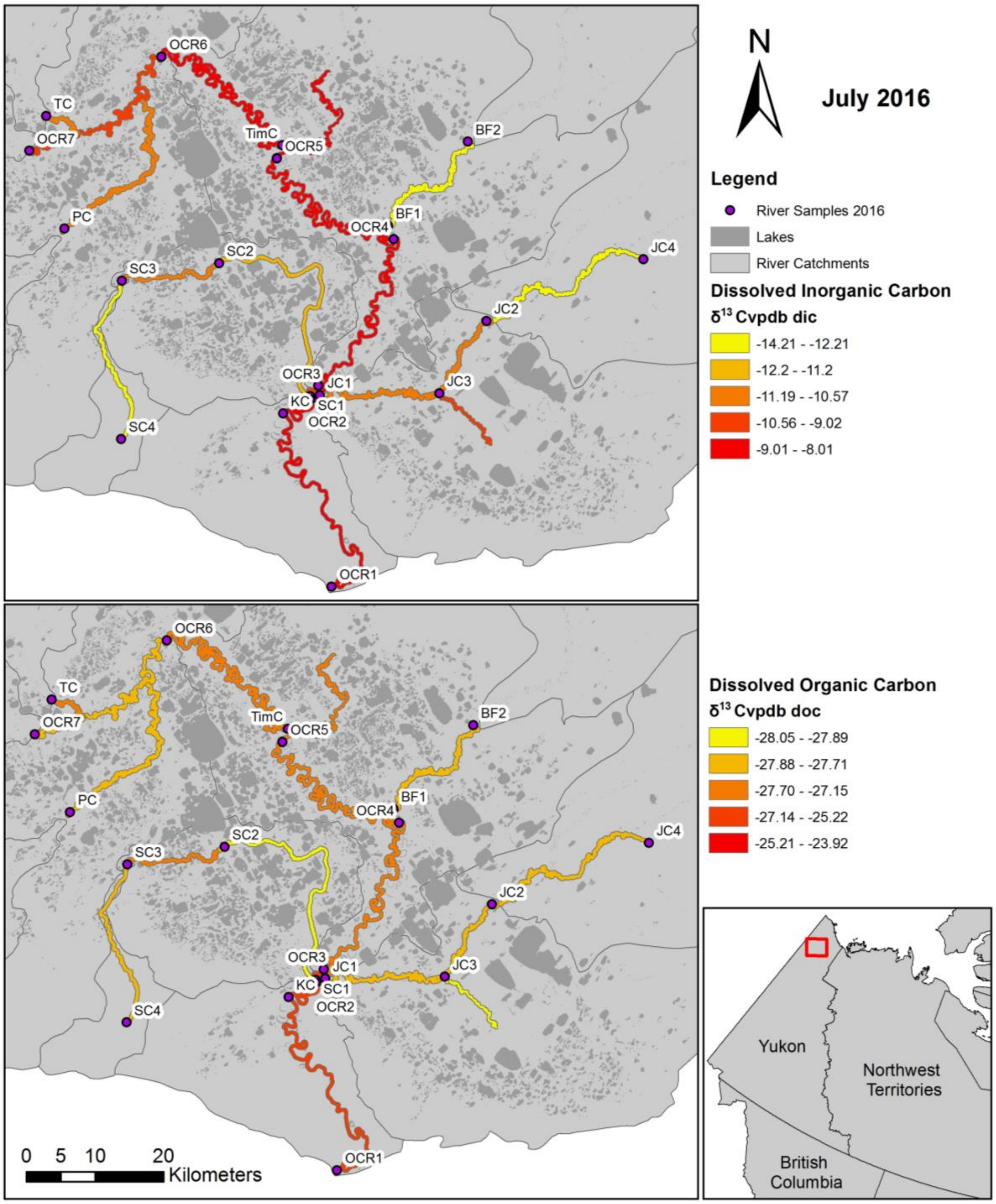



*Figure 3.6. Dissolved inorganic and organic isotope signatures ($\delta^{13}C$) and movement throughout OCF and the major river networks during July 2016.*

Lake water carbon concentrations and isotope signatures over July 2015 and 2016 (Table 3.1) are highly variable across OCF. River and creek carbon concentrations cannot be used to clearly identify lake water contributions given the high variability of concentrations among lakes. Collecting a greater number of samples and confining those to within each river catchment would result in a more localized indication of lake carbon concentrations and possible impact on the river system.

*Table 3.1. Carbon results from 12 lakes sampled during July 2015 and 14 lakes during July 2016 across OCF. Data displays variability in lake carbon concentrations and isotope signatures. The average lake concentrations and signatures have been used to identify possible impact on river carbon.*

| | **DOC (ppm)** | **$\delta^{13}$C DOC** | **DIC (ppm)** | **$\delta^{13}$C DIC** |
|---|---|---|---|---|
| **Lakes 2015** | | | | |
| Average | 14.1 | -26.1 | 14.6 | -10.2 |
| St. Dev | 5.2 | 1.5 | 12.7 | 6.9 |
| Max | 21.0 | -23.5 | 50.0 | 0.7 |
| Min | 3.9 | -28.4 | 2.7 | -20.5 |
| **Lakes 2016** | | | | |
| Average | 14.7 | -25.7 | 10.3 | -8.0 |
| St. Dev | 4.8 | 1.9 | 6.1 | 4.6 |
| Max | 21.6 | -22.1 | 23.9 | 1.0 |
| Min | 7.9 | -28.3 | 1.8 | -17.4 |

### 3.4.2 Impact of a retrogressive thaw slump on river water carbon

A new retrogressive thaw slump initially exported a large volume (~29,000 $m^3$) of debris into the Old Crow River between May 26th and July 26th 2016. Results from the DIC and DOC concentrations (ppm) and isotope signatures ($\delta^{13}$C) were plotted to highlight the impact of the retrogressive thaw slump on carbon export and mobility as well as identify seasonal and inter-annual variability in carbon export across OCF from other sources. Each major tributary has a single or multiple sample points which connect to the Old Crow River indicating their influence on the overall river water carbon balance.

Samples processed for DOC concentrations during July 2015 and 2016 show similar spatial patterns across all major tributaries (Figure 3.7). The two years both show the Old Crow River DOC concentration increasing downriver with the larger southern tributary (JC) having the greatest influence ~75 km north of the Old Crow River mouth. KC shows the highest DOC concentrations of 19.4 ppm (July 2015) and 27.3 ppm (July 2016). Runoff from the active retrogressive thaw slump was sampled during a rainfall event in July 2016. The retrogressive thaw slump (SR) had runoff water with the second highest DOC concentration across OCF (22.2 ppm), and has an impact on the Old Crow River, increasing its DOC concentration slightly in 2016 (10.1 to 12.1 ppm). Once the large southern tributaries (JC, SC) connect, JC decreases DOC concentrations in the Old Crow River, while SC shows to have little to no impact on the Old Crow River prior to leaving OCF.

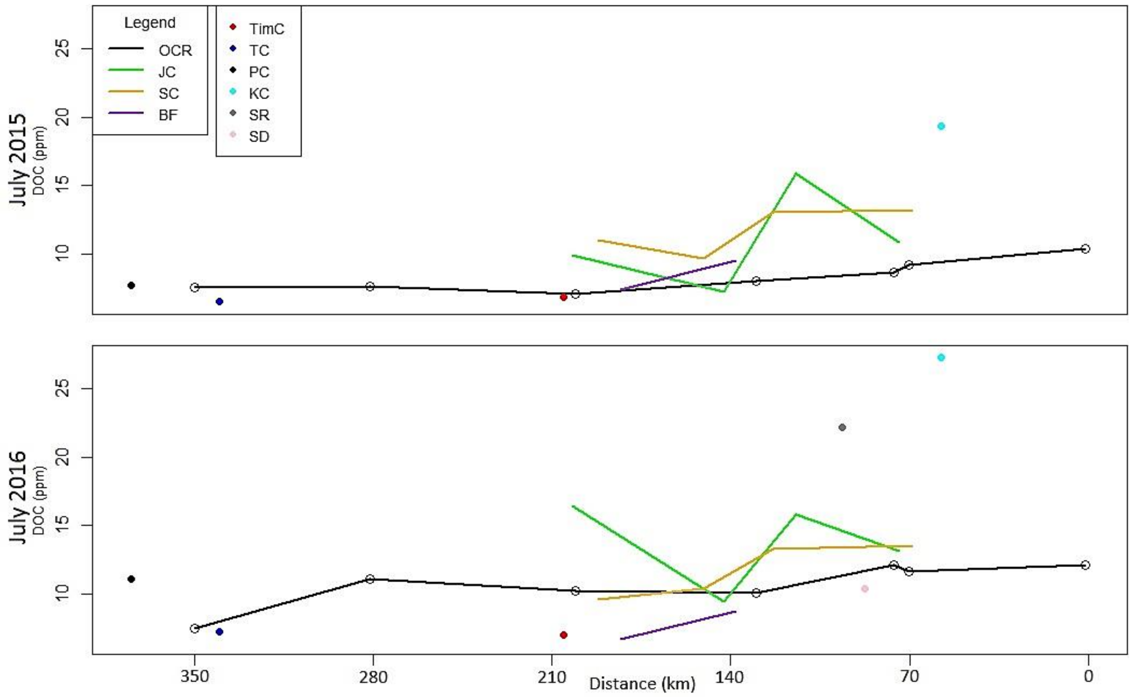



*Figure 3.7. Dissolved organic carbon concentrations (ppm) from headwater (left) to where the Old Crow River (OCR) exits OCF (right) for July 2015 and 2016. Results show the influence of an active retrogressive thaw slump (SR, grey circle) on the main Old Crow River. Rivers with multiple samples are shown as lines and rivers with a single sample are shown as circles.*

Samples processed for DIC concentrations during July 2015 and 2016 also show similar spatial patterns from both years (Figure 3.8). DIC decreases from the headwater (46.6 ppm, 28.7 ppm; 2015 and 2016 respectively) to where the Old Crow River exits OCF (0 km; 20.3 ppm, 18.0 ppm for 2015 and 2016 respectively) and displays a noticeable drop in concentration where the southern tributary connects (JC; ~75 km) (Figure 3.8). The retrogressive thaw slump runoff sample (July 2016) plots just above the Old Crow River and contains very similar DIC concentrations to the river, suggesting little influence on the overall decreasing Old Crow River concentration. This indicates that water sampled from the thaw slump runoff had very similar DIC concentrations as the river water and, hence, had little influence on it. DIC concentrations exported to this point in the OCF basin is likely dominated by erosional processes. Lake water outflow evidently had a greater influence on the DIC concentrations during 2015.

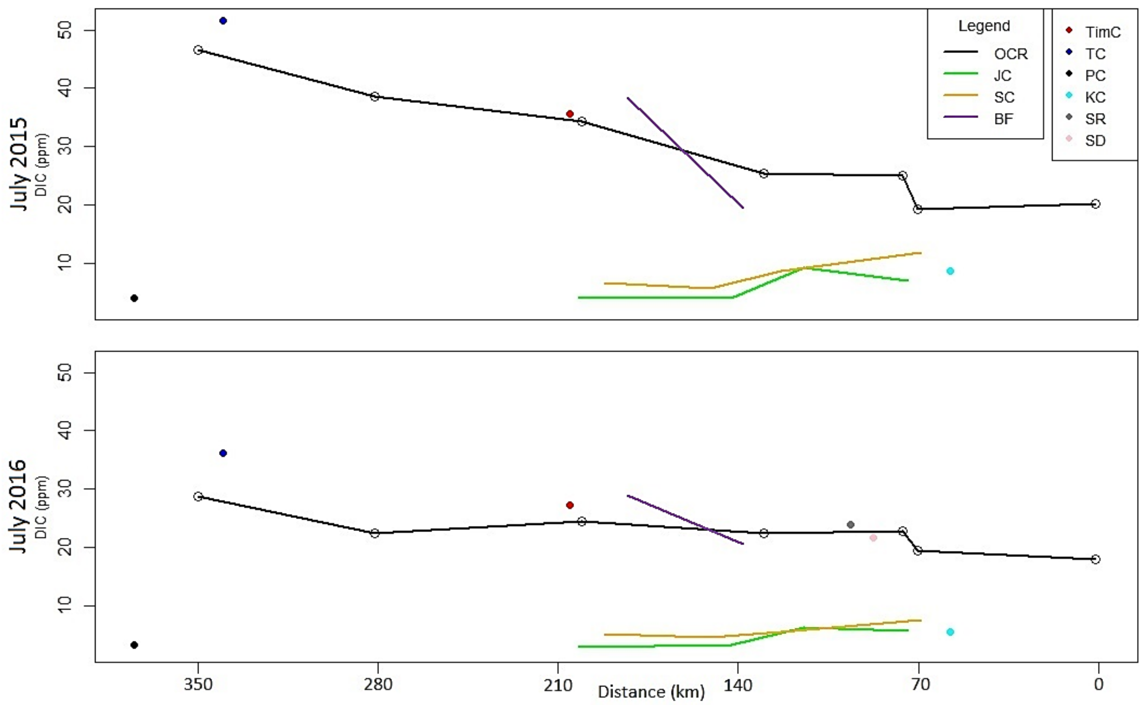



*Figure 3.8. Dissolved inorganic carbon concentrations (ppm) from headwater (left) to where the Old Crow River (OCR) exits OCF (right) for July 2015 and 2016. Results show the influence of an active retrogressive thaw slump (SR, grey circle) on the main Old Crow River. Rivers with multiple samples are shown as lines and rivers with a single sample are shown as circles.*

Results for the $\delta^{13}C$ DOC show the largest inter-annual variability from 2015 to 2016 (Figure 3.9). There is a decrease in concentration through the Old Crow River during 2015 where JC and SC have the largest influence on the isotope signature, whereas 2016 has increasing concentrations downriver. The resulting difference is likely due to the addition of the retrogressive thaw slump (-25.3‰) which connects to the Old Crow River where the largest jump in isotope signature can bee seen (~80 km; July 2016). Downstream from that point, the Old Crow River begins to decrease again from the input of the southern tributaries, which dilute the $\delta^{13}C$ DOC signature. The Old Crow River headwater sites (OCR7; ~ 350 km) also vary from 2015 to 2016 (-23.9, -27.8

respectively), however, this variability is still unknown and highlights that future research should include headwater landscape conditions for understanding source water variability.

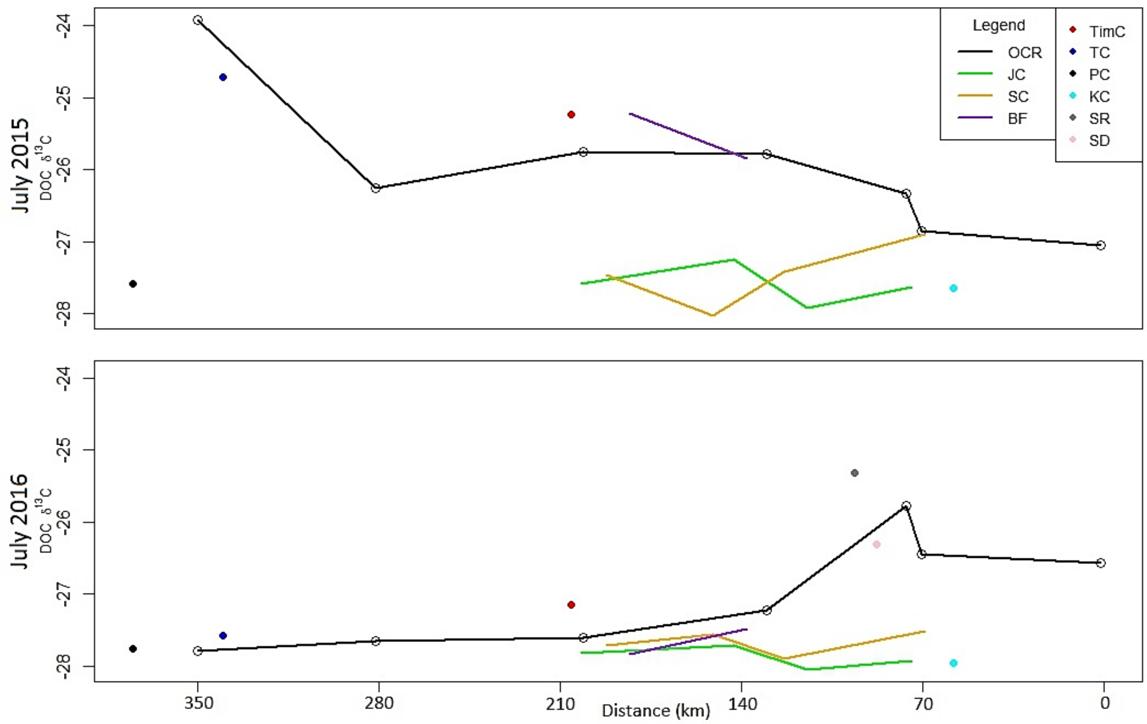



*Figure 3.9. Dissolved organic carbon isotope signatures (δ$^{13}$C) from headwater (left) to where the Old Crow River (OCR) exits OCF (right) for July 2015 and 2016. Results show the influence of an active retrogressive thaw slump (SR, grey circle) on the main Old Crow River. Rivers with multiple samples are shown as lines and rivers with a single sample are shown as circles.*

Results of δ$^{13}$C DIC from water samples collected in 2015 and 2016 show the least inter-annual variability with little change in δ$^{13}$C DIC concentration along the Old Crow River from the headwaters to where Old Crow River exits OCF (Figure 3.10). In 2015, the samples with the lowest δ$^{13}$C DIC values are the tributary headwaters (PC, JC4, SC4, BF2), which seem to have little impact on the Old Crow River. There is a slight decrease in 2015 where JC connects, but overall the isotope signature remains stable. In 2016, the retrogressive thaw slump has the highest signature (-6.9‰), but seems to show no effect on the δ$^{13}$C DIC signature of the Old Crow River. The lowest signature during

July 2016 is KC at -13.4‰, but this tributary also appears to show little impact on the Old Crow River. The headwater samples have slightly higher isotope signatures during 2016, which could be due to increased precipitation and runoff diluting the results.

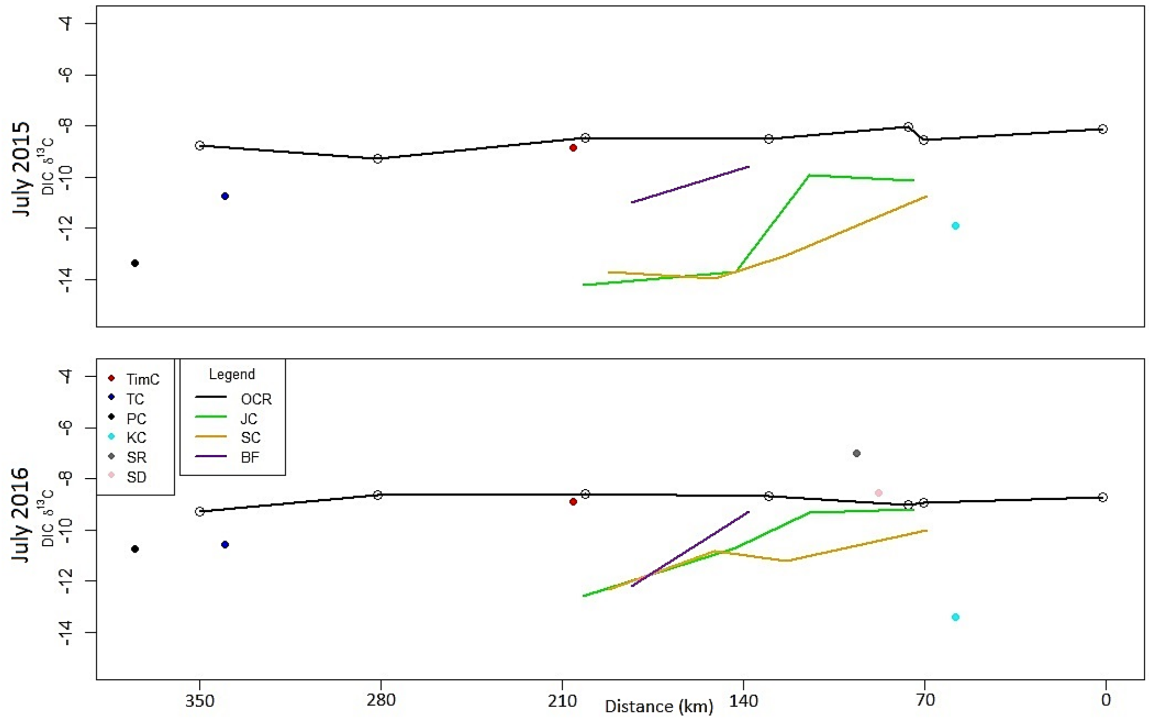



*Figure 3.10. Dissolved inorganic carbon isotope signatures ($\delta^{13}C$) from headwater (left) to where the Old Crow River (OCR) exits OCF (right) for July 2015 and 2016. Results show the influence of an active retrogressive thaw slump (SR, grey circle) on the main Old Crow River. Rivers with multiple samples are shown as lines and rivers with a single sample are shown as circles.*

Samples from May 2016 across all carbon signatures show little downriver change (Figure 3.11). DOC (ppm) is decreasing from the most northern sample (OCR5.5: 17.7 ppm) to the end of the Old Crow River (OCR1: 13.8 ppm). The most southern tributary (KC) has the greatest concentration (19.4 ppm), but shows what could be a slight influence on the Old Crow River. The results for DIC concentrations and $\delta^{13}C$ DOC both appears not to change downriver, but the southern tributaries (SC, JC, KC) plot below the Old Crow River across both variables. Finally, $\delta^{13}C$ DIC also has little overall downriver change, but does appear to drop due to the connection of JC (-15.1‰), which besides KC (-15.4‰), is the lowest $\delta^{13}C$ DIC signature recorded over all three sampling periods.

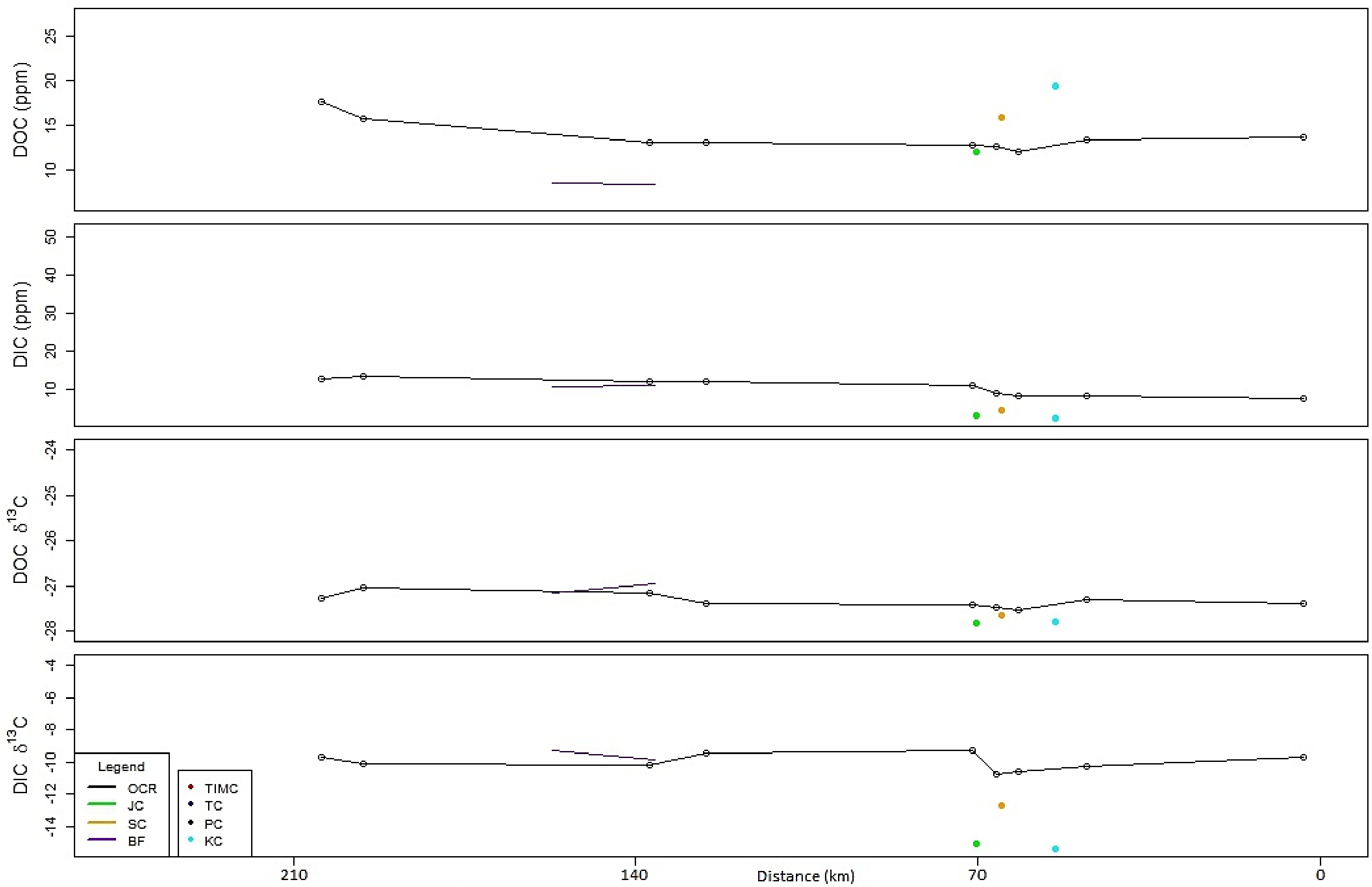



*Figure 3.11. Carbon concentrations (DIC, DOC) and isotope signatures ($\delta^{13}C$ DIC and DOC) for May 2016.*

To highlight the variability of the slump sample runoff as compared to the local hydrology, a PCA was run on the water chemistry data collected during July 2016 (Figure 3.12). The retrogressive thaw slump sample (S1 runoff) plots far along the first and second PC axes as compared to all other lake and river sites. Higher concentrations of major ions and nutrients within the slump sample are shown by the water chemistry eigenvectors towards the bottom right of the PCA and the retrogressive thaw slump sample. With increased weathering and erosion from the retrogressive thaw slump, it is expected to have higher concentrations of weathering constituents (Mg, Na, K, Cl). On this PCA, DIC and DOC concentrations are found opposite one another along PC axis 1.

The water chemistry of the direct slump sample was found to contain elevated concentrations of almost all variables (Figure 3.13). This increase in nutrients and ions from the retrogressive thaw slump appear to have little to no impact on the downriver water chemistry of the Old Crow River, as compared to changes in water chemistry along tributaries such as increases in nutrients (TDN, TN) along SC and increases in both major ions (Cl, SO4, Na) and nutrients (TDN, TN) along JC. Opposed to changes in $\delta^{13}$C DIC from the retrogressive thaw slump as mentioned above, the Old Crow River water chemistry likely changes from other sources such as surrounding landscape runoff, lake water input, and its major tributaries.

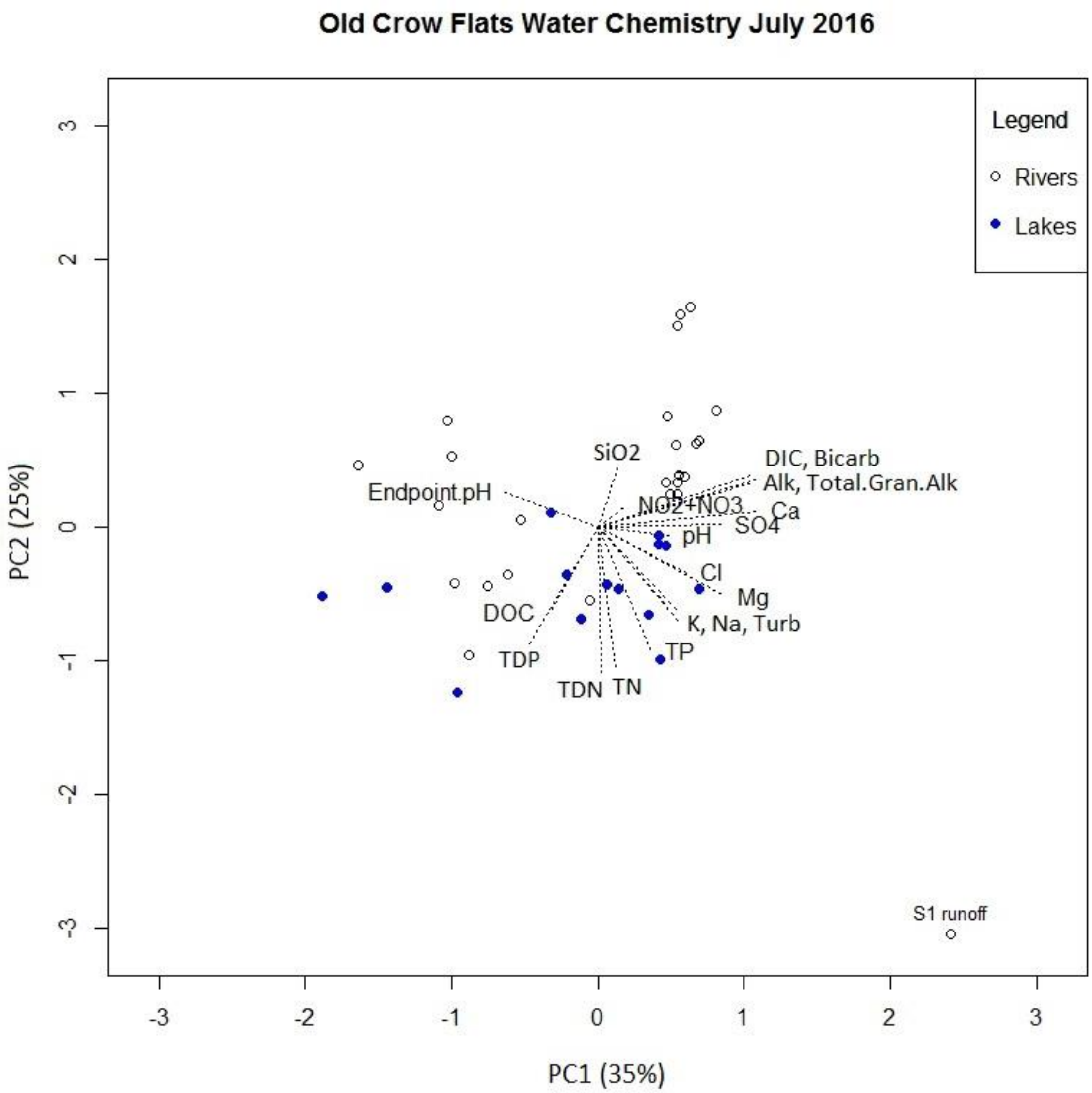



*Figure 3.12. Principal component analysis biplot (PCA) which indicates the high level of variance between the slump sample (S1 runoff) and the rest of the lake and river sample sites across OCF taken during the July 2016 sampling period. The retrogressive thaw slump is highly correlated to a group of the major ions (K, Na, Mg and Cl) (Appendix A).*

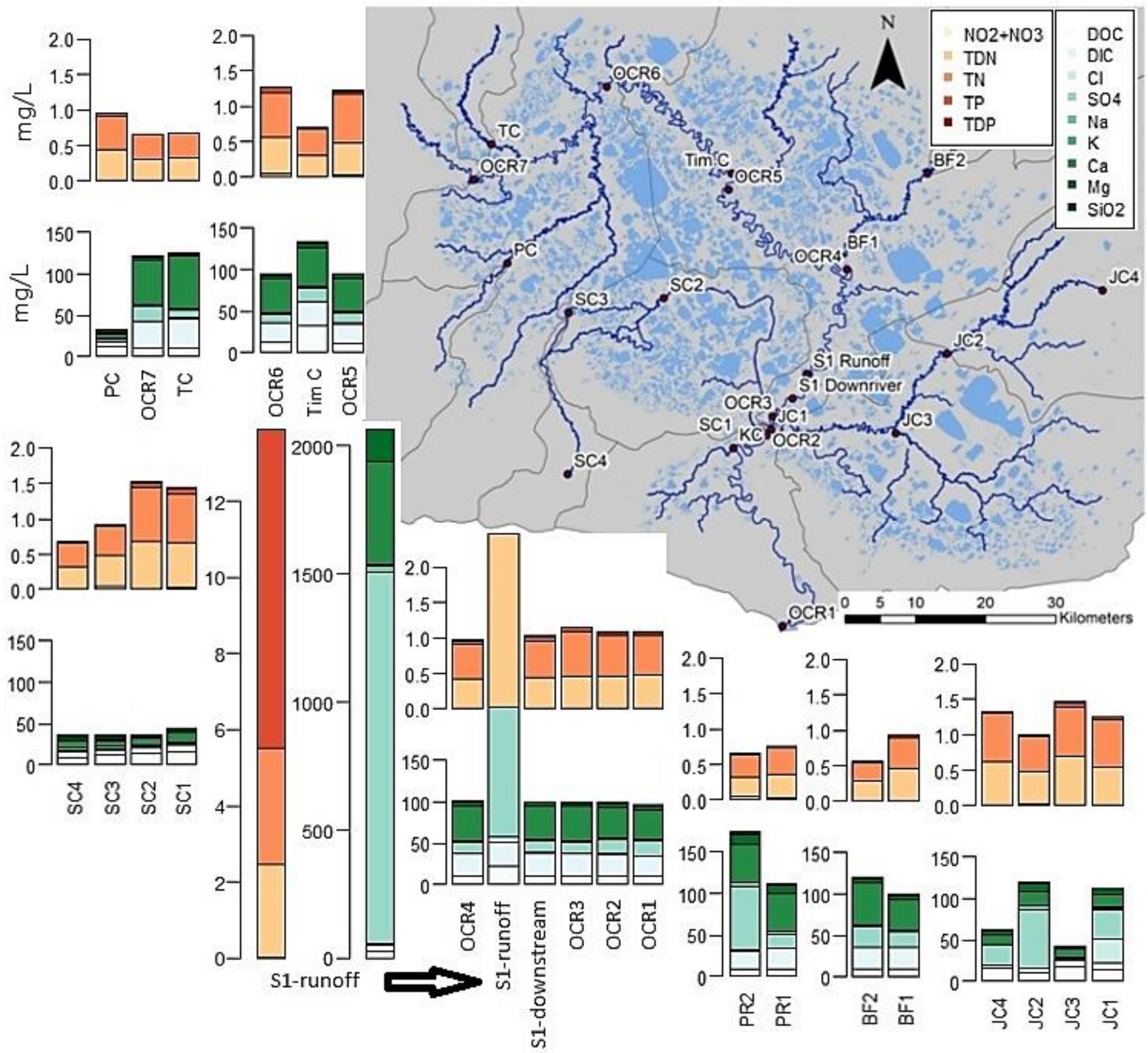


*Figure 3.13. Water chemistry data from July 2016 with separated nutrients and major ions, as well as split across OCF to highlight spatial variability across tributaries. Each plot is split among tributaries and section of the hydrology from headwater (left) to downriver samples (right). Y-axis concentrations for all plots are in mg/L.*

## 3.5 Discussion

Carbon concentrations and isotope signatures across OCF provide insight into the spatial variability and major landscape level impacts on carbon export through the hydrologic system. Carbon export in 2015 and 2016 was spatially variable between creeks and rivers across OCF, however, landscape changes that occur across OCF such as retrogressive thaw slumps can have an effect on the water chemistry. Previous research has identified the general drivers of varying river inputs (snowmelt, rain, and lake water) and catchment characteristics impacting lake water (Turner et al., 2010, 2014b, 2014a). Increasing frequency of landscape level changes such as lake drainage events (Turner et al., 2010), and retrogressive thaw slumps (Lantz and Kokelj, 2008) can also impact river water chemistry, as well as carbon export and biodegradability (Abbott et al., 2014; Spencer et al., 2015). This study expands off previous work in OCF to enhance our understanding of carbon export and mobility across this large Arctic headwater basin using a suite of water chemistry parameters. Of particular interest was identifying spatial variation in DIC and DOC concentrations and isotope signatures across the drainage network. As well, how DIC and DOC concentration and isotope signatures were influenced by landscape features including thaw slumps and lakes. Landscape changes such as retrogressive thaw slumps and lake drainages could also continue to increase in frequency across the Arctic and within OCF (Lantz and Kokelj, 2008, Lantz and Turner, 2015), increasing their impact on the hydrology. The aim is to enhance our understanding of how changing climate may continue to impact the local carbon budget and downstream conditions.

Carbon mobility through OCF is seasonally and inter-annually variable over the two sample years (July 2015, to May 2016, to July 2016), and highlights our ability to distinguish landscape and seasonal impacts on the local hydrologic carbon budget. Lateral lake drainage (Mackay, 1988; Hinkel et al., 2007; Marsh et al., 2009) and thaw features such as retrogressive thaw slumps can also alter concentrations of solutes and nutrients in the local hydrologic systems such as lakes and rivers (Bowden et al., 2008; Kokelj et al., 2009). Research presented here provides a baseline understanding of the hydrology, which is expected to change concurrently with continued lake drainages and thaw slumps. This research also highlights changes in carbon export within a headwater basin which could feed larger Arctic river systems that export into the Arctic Ocean (Tank et al., 2012a; 2012b) and enhance our understanding of carbon sourcing through the Arctic hydrological system. During July 2015, the OCF headwater samples contain the highest concentrations of DIC and the lowest DOC whereas the opposite can be said for the southern tributaries. July 2016 DIC/DOC concentrations show very similar results, which is likely due to unchanged surrounding landscape catchment characteristics which influence the hydrology on an annual scale. DIC is greatest in the northern tributaries, where the catchments are dominated by tundra and the rivers are mainly runoff fed. DOC is greatest in the southern tributaries, which tend to have more shrub coverage and greater lake-to-river connectivity. The Schaeffer Creek segment between SC3 and SC2 runs directly through a lake, which in turn increases the DOC concentration in 2015 and 2016. These sample concentrations of DOC may also vary based on the level of biodegradability that could vary from site to site and sample to sample across OCF and could be lost in headwater systems prior to leaving OCF (Vonk et al., 2015; Spencer et al., 2015). Erosional features observed across Arctic landscapes such as expansion of channel networks (Toniolo et al., 2009), increased river bank erosion (Costard et al., 2007), and increasing rates of retrogressive thaw slumps (Lantz and Kokelj, 2008) also impact the spatial variability in $\delta^{13}C$ DIC and $\delta^{13}C$ DOC across OCF. Increased riverbank erosion along northern tributaries and the main Old Crow River show increased carbon isotope signatures during both 2015 and 2016, which was pronounced following initiation of a retrogressive thaw slump event.

Retrogressive thaw slumps have been shown to impact local water chemistry (Kokelj et al., 2009) and biological productivity (Thienpont et al., 2013) in lakes across other ice-rich permafrost environments. The addition of a retrogressive thaw slump along the Old Crow River during 2016 appears to have the greatest influence on the DOC concentrations and $\delta^{13}$C DIC and $\delta^{13}$C DOC signatures (Figures 3.7-3.10). DOC concentrations from the retrogressive thaw slump direct runoff is the second highest (~22 ppm) and could be increasing the Old Crow River values prior to the confluence of JC and SC. This is likely due to organic carbon trapped within the permafrost, which became available for mobilization during export of the slump debris. Additionally, the ongoing thaw of the cut bank could continue to add organic carbon through groundwater and overland flow. There was also a large amount of debris deposited in the river which would slowly be eroded and alter the river water chemistry depending on the magnitude of flow (Figure 3.2). These features have also been shown to have major impacts on the DOC export and biodegradability in Arctic river systems (Abbott et al., 2014), which could indicate that large amounts of DOC are being mineralized and released as $CO_2$ within this headwater river system (Vonk et al., 2015) prior to leave OCF. Isotope signatures for DIC are also elevated from the retrogressive thaw slump, but seem to show no effect on the Old Crow River. The stability of the isotope signature of DIC could be due to efficient dilution of any added material from the thaw slump and a low erosive ability of the material in the river. Finally, as mentioned above, the largest inter-annual variation was in $\delta^{13}$C DOC (Figure 3.9). The retrogressive thaw slump increases the $\delta^{13}$C DOC signature in the Old Crow River, that is likely slump debris slowly being reworked along with continual weathering and runoff from the slump scar. The thawing of previously frozen DOC within the permafrost is likely increasing the Old Crow River's isotope signature from -28‰ to -26‰.

Samples collected during May (2016) highlight carbon export during freshet, where water is at its highest due to increased snowmelt and precipitation. DOC concentrations are their greatest during this melt period in the headwaters (OCR5 and above), which is likely due to increased influx of lake water and runoff. DIC concentrations are lowest during this period and remain fairly stable across OCF. This is likely due to the continuing low temperatures that minimize permafrost thaw and active layer depth, which minimizes chemical weathering and the addition of DIC. The isotope signatures for DOC are consistently low, which indicates that spatial landscape variability has little influence on the spring melt DOC source whereas we see much greater variability in summer samples from July 2015 and 2016. Finally, the isotope signatures for DIC have some of the lowest signatures of all samples (JC and KC), but have very little influence on the Old Crow River, which is stable downriver. These samples also are during freshet, which means they are exporting more water from OCF into the Porcupine River, which is carried further into the Yukon River and eventually into the Arctic Ocean. The addition of discharge data with further research into carbon mobility and export would increase our ability to understand the impact this headwater basin may be having on downriver systems.

Later carbon export along river systems is spatially variable and dependant on catchment characteristics, changing climate, and landscape alterations. Thaw features such as retrogressive thaw slumps (Kokelj et al., 2009) and active layer detachment slides (Lamoureux et al., 2014; Lamhonwah et al., 2017) have been shown to impact local

Arctic water chemistry through mobilization of previously frozen sediments. With permafrost landscapes thought to hold over 50% of the terrestrial organic carbon (Tarnocai et al., 2009; Hugelius et al., 2014), these features could increase the mobility of carbon through the hydrology across Arctic permafrost regions (Spencer et al., 2015; Schuur et al., 2015). The largest influence on carbon export through OCF seems to be lake water that is likely due to greater concentrations of lake-to-river connectivity in southern OCF (Chapter 2). The addition of lake water increases DOC along the major tributaries and dilutes the DIC once connected to the Old Crow River. The retrogressive thaw slump seems to have the largest impact on $\delta^{13}C$ DOC signatures and is highly correlated to potassium, sodium and magnesium, which is likely related to the weathering of previously frozen material. Apart from $\delta^{13}C$ DOC, the retrogressive thaw slump does not appear to alter downriver water chemistry. This result appears distinct from other research where retrogressive thaw slumps appear to impact local lake water chemistry (Kokelj et al., 2009), however this slump resides on a large river that likely exports the majority of added debris quickly. This minimizes its impact on the local water chemistry after the initial event, however, continued slump erosion or reworking of debris left in the river channel could continue to impact the water chemistry. With continuing landscape changes and possible increases in retrogressive thaw slumps throughout these ice-rich permafrost environments (Lantz and Kokelj, 2008) it is important to understand the potential influences these features have on the Arctic hydrology, carbon export and mobility. This increase could also impact $CO_2$ release through mineralization and the local carbon budget of these headwater systems.

## 3.6 Conclusions

Arctic aquatic environments have undergone landscape changes such as lake drainage events (Lantz and Turner, 2015), expansion of channel networks (Toniolo et al., 2009), increased riverbank erosion (Costard et al., 2007) and retrogressive thaw slumps (Lantz and Kokelj, 2008). These changes have an impact on water chemistry, nutrient and sediment loading along with concentrations of trapped organic carbon which could become available for mineralization (Schuur et al., 2015). From this research, spatial variability in land cover and landscape changes appear to be crucial in understanding carbon export through the hydrology across Arctic landscapes. Across OCF, the northern headwaters are dominated by runoff and have higher DIC concentrations and isotope signatures, whereas the southern tributaries contain higher DOC concentrations because of increased lake-to-river connectivity and surrounding shrub cover. Sampling of an active retrogressive thaw slump highlights the influence of landscape alterations by having the greatest influence on the $\delta^{13}C$ DOC along the Old Crow River, that is likely organic carbon that was previously frozen within the permafrost and became mobilized within the hydrology. Collecting a larger set of lake $\delta^{13}C$ DOC signatures and continued monitoring along the Old Crow River would enhance our understanding of separation between lake versus slump $\delta^{13}C$ DOC signatures. Changes in $\delta^{13}C$ DOC along the Old Crow River could be used to identify upstream climate induced landscape changes such as increases in retrogressive thaws slumps or lake drainage events.

Studying the local Arctic carbon budget requires an understanding of multiple landscape factors, such as organic and inorganic carbon storage in permafrost soils and its susceptibility to mineralization, as well as $CO_2$ sequestration through weathering constituents (Tank et al., 2012a, 2012b; Abbott et al., 2014). This study highlights that across OCF the overall DOC export seems to be dominated by lake-to-river connections and surrounding shrub cover in the south, that has been shown by the southern tributaries having greater lake-to-river connectivity and nutrient load (Chapter 2). However, with increases in landscape disturbances, especially the frequency of retrogressive thaw slumps, previously trapped carbon could become available for export and increase the level of mineralization within the headwater basin or downriver and into the Arctic Ocean (Abbott et al., 2014; Schuur et al., 2015; Spencer et al., 2015). Also, continued increases in catastrophic lake drainages (Lantz and Turner, 2015) could continue to or increase the export of carbon into the river network and out of OCF. Ongoing research into possible $CO_2$ sequestration through carbonate and silicate weathering (Lerman et al., 2007), sulfide oxidation (Tank et al., 2016), and the susceptibility of permafrost derived DOC to mineralization (Abbott et al., 2014; Schuur et al., 2015; Spencer et al., 2015) will build a more complete carbon balance model and enhance our understanding of the OCF headwater carbon cycle.

## 3.7 References

Abbott, B.W., Larouche, J.R., Jones, J.B., Bowden, W.B., Balser, A.W., 2014. Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost: Permafrost carbon biodegradability. J. Geophys. Res. Biogeosciences 119, 2049–2063. doi:10.1002/2014JG002678

Berner, E.K., Berner, R.A., 2012. Global environment: water, air, and geochemical cycles. Princeton University Press.

Bowden, W.B., Gooseff, M.N., Balser, A., Green, A., Peterson, B.J., Bradford, J., 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. J. Geophys. Res. Biogeosciences 113, n/a-n/a. doi:10.1029/2007JG000470

Brown, J., Ferrians, O., Heginbottom, J.A., Melnikov, E., 2002. Arctic map of permafrost and ground-ice conditions.

Brown, J., Sidlauskas, F.J., Delinski, G., 1997. Circum-Arctic map of permafrost and ground ice conditions.

Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Downing, J.A., Middelburg, J.J., Melack, J., 2007. Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget. Ecosystems 10, 172–185. doi:10.1007/s10021-006-9013-8

Cooper, L.W., McClelland, J.W., Holmes, R.M., Raymond, P.A., Gibson, J.J., Guay, C.K., Peterson, B.J., 2008. Flow-weighted values of runoff tracers ($\delta^{18}$O, DOC, Ba, alkalinity) from the six largest Arctic rivers. Geophys. Res. Lett. 35. doi:10.1029/2008GL035007

Costard, F., Gautier, E., Brunstein, D., Hammadi, J., Fedorov, A., Yang, D., Dupeyrat, L., 2007. Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia. Geophys. Res. Lett. 34. doi:10.1029/2007GL030212

Frontier, S., 1976. Etude de la décroissance des valeurs propres dans une analyse en composantes principales: comparaison avec le modèle du bâton brisé. J. Exp. Mar. Biol. Ecol. 25, 67–75.

Hindshaw, R.S., Lang, S.Q., Bernasconi, S.M., Heaton, T.H.E., Lindsay, M.R., Boyd, E.S., 2016. Origin and temporal variability of unusually low $\delta^{13}$ C-DOC values in two High Arctic catchments. J. Geophys. Res. Biogeosciences 121, 1073–1085. doi:10.1002/2015JG003303

Hinkel, K.M., Jones, B.M., Eisner, W.R., Cuomo, C.J., Beck, R.A., Frohn, R., 2007. Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska. J. Geophys. Res. 112. doi:10.1029/2006JF000584

Holmes, R.M., McClelland, J.W., Peterson, B.J., Tank, S.E., Bulygina, E., Eglinton, T.I., Gordeev, V.V., Gurtovaya, T.Y., Raymond, P.A., Repeta, D.J., Staples, R., Striegl, R.G., Zhulidov, A.V., Zimov, S.A., 2012. Seasonal and Annual Fluxes of Nutrients and Organic Matter from Large Rivers to the Arctic Ocean and Surrounding Seas. Estuaries Coasts 35, 369–382. doi:10.1007/s12237-011-9386-6

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.L., Schirrmeister, L., Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., Kuhry, P., 2014.

Improved estimates show large circumpolar stocks of permafrost carbon while quantifying substantial uncertainty ranges and identifying remaining data gaps. Biogeosciences Discuss. 11, 4771–4822. doi:10.5194/bgd-11-4771-2014

Hughes, O.L., 1972. Surficial geology of northern Yukon Territory and northwestern district of Mackenzie Northwest Territories (Paper No. 69–36). Geological Survey of Canada.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC fifth assessment report. Cambridge Univ. Press, Cambridge, UK.

Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Walter Anthony, K.M., Romanovsky, V.E., 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. J. Geophys. Res. 116. doi:10.1029/2011JG001666

Jorgenson, M.T., Racine, C.H., Walters, J.C., Osterkamp, T.E., 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Clim. Change 48, 551–579.

Kokelj, S.V., Zajdlik, B., Thompson, M.S., 2009. The impacts of thawing permafrost on the chemistry of lakes across the subarctic boreal-tundra transition, Mackenzie Delta region, Canada. Permafr. Periglac. Process. 20, 185–199. doi:10.1002/ppp.641

Labrecque, S., Lacelle, D., Duguay, C.R., Lauriol, B., Hawkings, J., 2009. Contemporary (1951-2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: Remote sensing, numerical modeling, and stable isotope analysis. Arctic 225–238.

Lafrenière, M.J., Louiseize, N.L., Lamoureux, S.F., 2017. Active layer slope disturbances affect seasonality and composition of dissolved nitrogen export from High Arctic headwater catchments. Arct. Sci. 3, 429–450. doi:10.1139/as-2015-0009

Lamhonwah, D., Lafrenière, M.J., Lamoureux, S.F., Wolfe, B.B., 2017. Multi-year impacts of permafrost disturbance and thermal perturbation on High Arctic stream chemistry. Arct. Sci. 3, 254–276. doi:10.1139/as-2016-0024

Lamoureux, S.F., Lafrenière, M.J., Favaro, E.A., 2014. Erosion dynamics following localized permafrost slope disturbances. Geophys. Res. Lett. 41, 5499–5505. doi:10.1002/2014GL060677

Lantz, T.C., Kokelj, S.V., 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophys. Res. Lett. 35. doi:10.1029/2007GL032433

Lantz, T.C., Turner, K.W., 2015. Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. J. Geophys. Res. Biogeosciences 120, 513–524. doi:10.1002/2014JG002744

Lauriol, B., Duguay, C.R., Riel, A., 2002. Response of the Porcupine and Old Crow rivers in northern Yukon, Canada, to Holocene climatic change. The Holocene 12, 27–34. doi:10.1191/0959683602hl517rp

Legendre, P., Legendre, L., 1998. Numerical ecology, Second Edition. ed, Developments in Environmental Modelling. Elsevier.

Lerman, A., Wu, L., Mackenzie, F.T., 2007. CO2 and H2SO4 consumption in weathering and material transport to the ocean, and their role in the global carbon balance. Mar. Chem. 106, 326–350. doi:10.1016/j.marchem.2006.04.004

Li, S.-L., Liu, C.-Q., Li, J., Lang, Y.-C., Ding, H., Li, L., 2010. Geochemistry of dissolved inorganic carbon and carbonate weathering in a small typical karstic catchment of Southwest China: Isotopic and chemical constraints. Chem. Geol. 277, 301–309. doi:10.1016/j.chemgeo.2010.08.013

Mackay, J.R., 1988. Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie. Geol. Surv. Can. 88–1D, 83–90.

Marsh, P., Russell, M., Pohl, S., Haywood, H., Onclin, C., 2009. Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000. Hydrol. Process. 23, 145–158. doi:10.1002/hyp.7179

Morlan, R.., 1980. Taphonomy and archaeology in the Upper Pleistocene of the northern Yukon Territory: a glimpse of the peopling of the New World, Mercury series / National Museum of Man Paper / Archaeological Survey of Canada; no. 94 Mercury series.

Morlan, R.E., 2003. Current perspectives on the Pleistocene archaeology of eastern Beringia. Quat. Res. 60, 123–132. doi:10.1016/S0033-5894(03)00070-X

OI Analytical, 2005. Aurora 1030 Wet Oxidation TOC analyzer Operator's Manual.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2018. Package "vegan." Community ecology package, version 2.

O'Leary, M.H., 1988. Carbon Isotopes in Photosynthesis. BioScience 38, 328–336. doi:10.2307/1310735

Raymond, P.A., McClelland, J.W., Holmes, R.M., Zhulidov, A.V., Mull, K., Peterson, B.J., Striegl, R.G., Aiken, G.R., Gurtovaya, T.Y., 2007. Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest arctic rivers. Glob. Biogeochem. Cycles 21, n/a-n/a. doi:10.1029/2007GB002934

Riordan, B., Verbyla, D., McGuire, A.D., 2006. Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. J. Geophys. Res. Biogeosciences 111. doi:10.1029/2005JG000150

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., Olefeldt, D., Romanovsky, V.E., Schaefer, K., Turetsky, M.R., Treat, C.C., Vonk, J.E., 2015. Climate change and the permafrost carbon feedback. Nature 520, 171–179. doi:10.1038/nature14338

Smith, L.C., Sheng, Y., MacDonald, G.M., Hinzman, L.D., 2005. Disappearing Arctic Lakes. Science 308, 1429.

Spencer, R.G.M., Aiken, G.R., Wickland, K.P., Striegl, R.G., Hernes, P.J., 2008. Seasonal and spatial variability in dissolved organic matter quantity and composition from the Yukon River basin, Alaska. Glob. Biogeochem. Cycles 22, n/a-n/a. doi:10.1029/2008GB003231

Spencer, R.G.M., Mann, P.J., Dittmar, T., Eglinton, T.I., McIntyre, C., Holmes, R.M., Zimov, N., Stubbins, A., 2015. Detecting the signature of permafrost thaw in Arctic rivers. Geophys. Res. Lett. 42, 2830–2835. doi:10.1002/2015GL063498

St-Jean, G., 2003. Automated quantitative and isotopic (13C) analysis of dissolved inorganic carbon and dissolved organic carbon in continuous-flow using a total organic carbon analyser. Rapid Commun. Mass Spectrom. 17, 419–428. doi:10.1002/rcm.926

Tank, S.E., Frey, K.E., Striegl, R.G., Raymond, P.A., Holmes, R.M., McClelland, J.W., Peterson, B.J., 2012a. Landscape-level controls on dissolved carbon flux from diverse catchments of the circumboreal. Glob. Biogeochem. Cycles 26, n/a-n/a. doi:10.1029/2012GB004299

Tank, S.E., Raymond, P.A., Striegl, R.G., McClelland, J.W., Holmes, R.M., Fiske, G.J., Peterson, B.J., 2012b. A land-to-ocean perspective on the magnitude, source and implication of DIC flux from major Arctic rivers to the Arctic Ocean: ARCTIC RIVER DIC. Glob. Biogeochem. Cycles 26, n/a-n/a. doi:10.1029/2011GB004192

Tank, S.E., Striegl, R.G., McClelland, J.W., Kokelj, S.V., 2016. Multi-decadal increases in dissolved organic carbon and alkalinity flux from the Mackenzie drainage basin to the Arctic Ocean. Environ. Res. Lett. 11, 054015. doi:10.1088/1748-9326/11/5/054015

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S., 2009. Soil organic carbon pools in the northern circumpolar permafrost region. Glob. Biogeochem. Cycles 23, n/a-n/a. doi:10.1029/2008GB003327

Thienpont, J.R., Rühland, K.M., Pisaric, M.F.J., Kokelj, S.V., Kimpe, L.E., Blais, J.M., Smol, J.P., 2013. Biological responses to permafrost thaw slumping in Canadian Arctic lakes: Aquatic biota response to permafrost thaw. Freshwater Biology 58, 337–353. https://doi.org/10.1111/fwb.12061

Toniolo, H., Kodial, P., Hinzman, L.D., Yoshikawa, K., 2009. Spatio-temporal evolution of a thermokarst in Interior Alaska. Cold Reg. Sci. Technol. 56, 39–49. doi:10.1016/j.coldregions.2008.09.007

Turner, K.W., Edwards, T.W.D., Wolfe, B.B., 2014a. Characterising Runoff Generation Processes in a Lake-Rich Thermokarst Landscape (Old Crow Flats, Yukon, Canada) using $\delta^{18}O$, $\delta^{2}H$ and d-excess Measurements: Characterising Runoff with Water Isotope Tracers in Old Crow Flats, Yukon. Permafr. Periglac. Process. 25, 53–59. doi:10.1002/ppp.1802

Turner, K.W., Wolfe, B.B., Edwards, T.W.D., 2010. Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. J. Hydrol. 386, 103–117. doi:10.1016/j.jhydrol.2010.03.012

Turner, K.W., Wolfe, B.B., Edwards, T.W.D., Lantz, T.C., Hall, R.I., Larocque, G., 2014b. Controls on water balance of shallow thermokarst lakes and their relations with catchment characteristics: a multi-year, landscape-scale assessment based on water isotope tracers and remote sensing in Old Crow Flats, Yukon (Canada). Glob. Change Biol. 20, 1585–1603. doi:10.1111/gcb.12465

Vonk, J.E., Tank, S.E., Mann, P.J., Spencer, R.G.M., Treat, C.C., Striegl, R.G., Abbott, B.W., Wickland, K.P., 2015. Biodegradability of dissolved organic carbon in permafrost soils and aquatic systems: a meta-analysis. Biogeosciences 12, 6915–6930. doi:10.5194/bg-12-6915-2015

Wang, Y., Huntington, T.G., Osher, L.J., Wassenaar, L.I., Trumbore, S.E., Amundson, R.G., Harden, J.W., McKnight, D.M., Schiff, S.L., Aiken, G.R., Lyons, W.B., Aravena, R.O., Baron, 1998. Carbon Cycling in Terrestrial Environments, in: Kendall, C., McDonnell, J.J. (Eds.), Isotope Tracers in Catchment Hydrology. Elsevier, pp. 577–610.

Wickland, K.P., Aiken, G.R., Butler, K., Dornblaser, M.M., Spencer, R.G.M., Striegl, R.G., 2012. Biodegradability of dissolved organic carbon in the Yukon River and its tributaries: Seasonality and importance of inorganic nitrogen. Glob. Biogeochem. Cycles 26, n/a-n/a. doi:10.1029/2012GB004342

Wolfe, B.B., Humphries, M.M., Pisaric, M.F., Balasubramaniam, A.M., Burn, C.R., Chan, L., Cooley, D., Froese, D.G., Graupe, S., Hall, R.I., others, 2011. Environmental change and traditional use of the Old Crow Flats in northern Canada: an IPY opportunity to meet the challenges of the new northern research paradigm. Arctic 64, 127.

Yang, C., Telmer, K., Veizer, J., 1996. Chemical dynamics of the “St. Lawrence” riverine system: δDH2O, δ18O H2O, δ13C DIC, δ34S sulfate, and dissolved 87Sr/ 86Sr. Geochim. Cosmochim. Acta 60, 851–866.

Zazula, G.D., Duk-Rodkin, A., Schweger, C.E., Morlan, R.E., 2004. Late Pleistocene chronology of Glacial Lake Old Crow and the north-west margin of the Laurentide ice sheet, in: Quaternary Glaciations-Extent and Chronology Part II: North America. Elsevier London, pp. 347–362.

Chapter 4:

# Concluding Remarks

## 4.1 Thesis Conclusions

It has been suggested that Arctic permafrost regions have been undergoing increased rates of landscape change due to climate alterations, but there is still a need to understand the drivers of change in the hydrology and influences on downriver basins. Previous research conducted on thermokarst lake hydrology focused on lake characteristics and lake area fluctuations (Smith et al., 2005; Riordan et al., 2006; Turner et al., 2010, 2014b, 2014a; Lantz and Turner, 2015) and identified variability in lake area reduction (Smith et al., 2005; Jones et al., 2011) together with spatial differences in lake water sourcing across thermokarst landscapes (Turner et al., 2010). Lake water sourcing is heavily influenced by surrounding catchment characteristics (Turner et al., 2014b) and with lake-to-river flow and increasing lake drainage events, can also impact river water (Turner et al., 2014a). This research expands our understanding of landscape influence on the hydrology across the OCF using a suite of water chemistry parameters and their influence on downriver systems. It also advances our understanding on how this hydrological system is responding to landscape conditions and creates a baseline for future research to detect subsequent changes.

Landscape disturbances also have ecological and geomorphological impacts that affect the overall river water chemistry, nutrient supply and sediment loading. Arctic landscapes have seen increases in erosional disturbances such as channel network expansion (Toniolo et al., 2009), riverbank erosion (Costard et al., 2007), retrogressive thaw slumps (Lantz and Kokelj, 2008) and active layer detachment slides (Lafrenière et al., 2017; Lamhonwah et al., 2017). Retrogressive thaw slumps can lead to the export of organic and mineral soils which have previously been frozen in the permafrost, impacting the local hydrology for potentially several decades (Kokelj et al., 2009; Kokelj and Jorgenson, 2013). Permafrost can also contain trapped organic carbon that could enter the local hydrology with increase thaw and affect the permafrost-carbon-feedback (Schuur et al., 2015). Studying the spatial variability in carbon sourcing and export can help understand changes in ecosystem dynamics from changes in landscape and climate.

To address these gaps, this research was conducted to:

1. Characterize lake-to-river connectivity across OCF using water isotope tracers.
2. Use a suite of water chemistry and isotope parameters to identify spatial variation in the influence of lake water export on river hydrology, including characterizing carbon export through DIC/DOC concentrations and $\delta^{13}C$ signatures.
3. Study the influence of a retrogressive thaw slump on the Old Crow River carbon balance.

The initial approach was to use water isotope tracers to identify lake-to-river connections across OCF over all sample periods and acquire a more complete understanding of seasonal and inter-annual variability. It was found that during the summer season (July 2015 and 2016), lake-to-river connections were much greater in the southern tributaries as compared to the north with higher isotope signatures from headwater catchments to downriver in the larger southern tributaries (SC, JC). The water chemistry also coincided with isotope signatures, where the southern tributaries plotted closer to the nutrients along with most lake samples, whereas the northern tributaries plotted closer to the major ions. The southern tributaries appear to have increased lake-to-river connections and greater influence from the surrounding shrub cover, whereas the northern tributaries mainly show increased concentrations of major ions via direct runoff and erosional processes.

The carbon concentrations and isotope signatures show a greater influence from lake water input than other landscape features, such as retrogressive thaw slumps. DOC (ppm) was much higher in the southern tributaries likely due to lake productivity and lake infiltration, whereas DIC (ppm) had higher concentrations in the northern tributaries and is likely dominated by landscape runoff and riverbank erosion. Isotope signatures for DIC and DOC ($\delta^{13}C$) are the greatest in the northern tributaries and the main Old Crow River, which are runoff fed, likely due to consistent riverbank erosion and mainly tundra vegetation. The larger southern tributaries have the lowest signatures for both DIC and DOC likely due to increased lake-to-river connections, abundance of shrub cover influencing $\delta^{13}C$ DOC, and less riverbank erosion altering $\delta^{13}C$ DIC. The retrogressive thaw slump runoff sampled during July 2016 did display higher concentrations of DOC (ppm) and increased isotope signatures of DIC and DOC, but seems to be overpowered in the hydrology by lake water infiltration and diluted within the Old Crow River. Continuing permafrost thaw and increasing retrogressive thaw slump events occurring along major river networks (Lantz and Kokelj, 2008) require continued research into their impact on the hydrology and carbon export. These landscape changes are also vial for understanding future implications on the local and global carbon budget.

## 4.2 Limitations

Throughout this research there have been a few limitations that need to be addressed. Lack of a meteorological station within the OCF means that weather data collected is from Old Crow, located ~25km south of OCF. Precipitation events, which could differ between Old Crow and the OCF could play a role in influencing changes in water chemistry and isotope signatures. Spatial differences in temperature can also play a role on landscape changes such as retrogressive thaw slumps, and lake or river water evaporation.

Another limitation is that this landscape is so large in area and contains such a dense river and lake network, so it is impossible at this stage to visually identify all of the hydrologic connections across OCF. Lake-to-river connections via overland flow can exist as small channels that are difficult to identify, and depending on active layer thickness, groundwater flow can also be a contributor throughout OCF. This study focused on the main river tributaries as a general indicator of spatial variability across OCF, which are more easily available to sample. Continued research into active layer thickness and talik formation across OCF could aid in our understanding of groundwater flow and possible permafrost thaw in the region. As well, higher resolution imagery across OCF could allow for identification of smaller lake-to-river connections as well as more landscape change events.

#### 4.2.1 Chlorophyll a

Chlorophyll a (Chl *a*) concentrations were analyzed from all sampling periods as a possible indicator of lake water influx (Figure 4.1). It was hypothesized that the stability of lake water would allow for increased productivity, and would show greater Chl *a* concentrations along rivers with increased lake-to-river connections. However, the data displayed very low concentrations from both lakes and rivers across OCF with little variability. The low concentrations across both lakes and rivers likely indicate an issue with the processing methods (as per Strickland and Parsons, 1972) from filters with such low concentrations (Stich and Brinker, 2005). Future processing should follow Stich and Brinker (2005) by testing HPLC, fluorometry and spectrometry, as well as whether acidification increases or decreases the accuracy of the Chl *a* results.

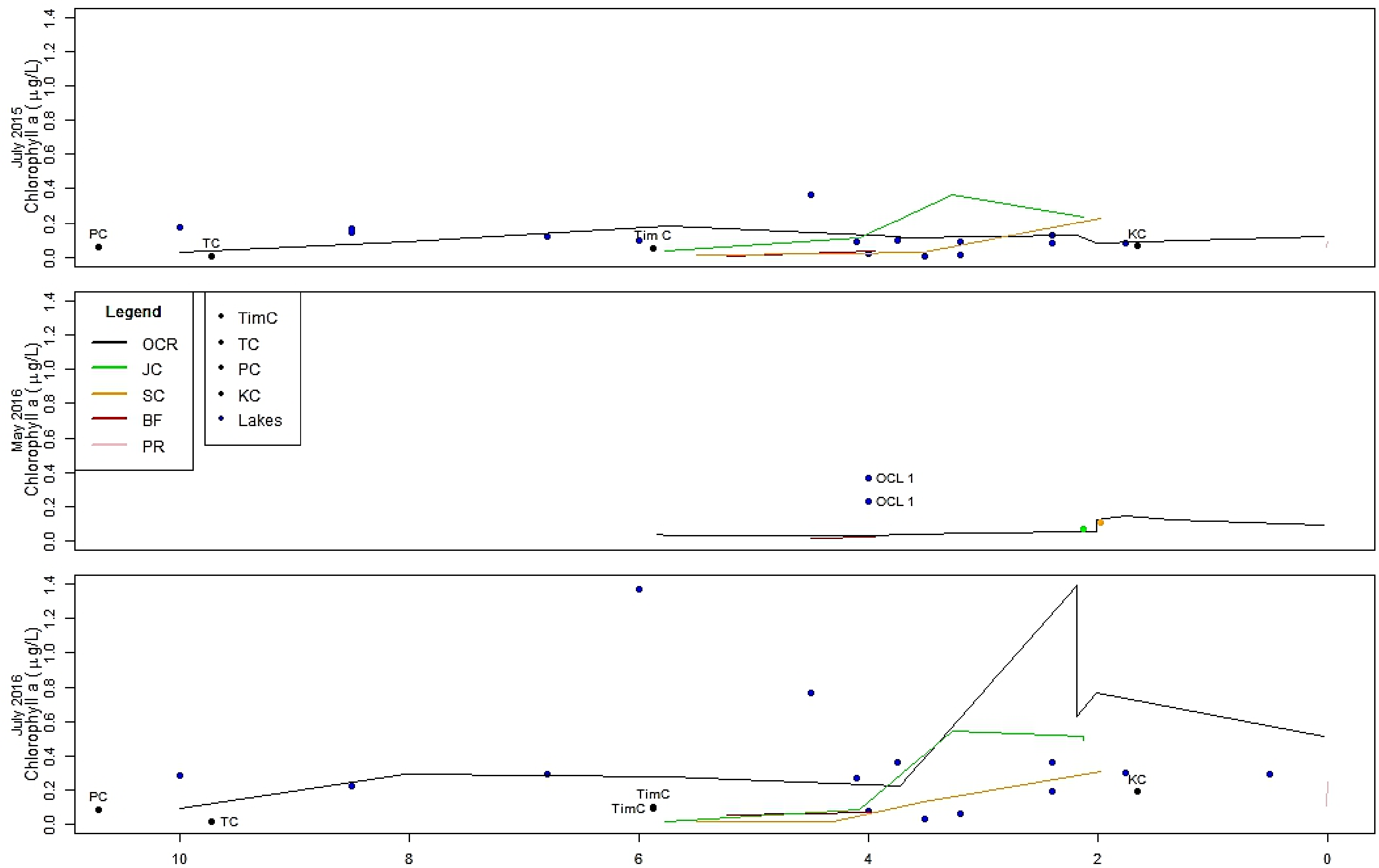



*Figure 4.1. Chlorophyll a concentrations (µg/L) from lake and river samples taken from July 2015, May 2016 and July 2016. Results show spatial variability across OCF as well as seasonal and annual variability. Lakes are plotted as blue points, rivers with only one sample are plotted as points and labeled, and rivers with multiple samples are plotted as lines indicating downriver change.*

## 4.3 Further Research

Continuing lake and river sampling could be coupled with these results to identify further landscape changes through the hydrology. Identifying shifts in isotope signatures, water chemistry parameters, or carbon concentrations could identify increases in lake-to-river connections or lake drainage events, along with increases in erosional features such as retrogressive thaw slumps along the river network. This could also lead to a monitoring protocol that requires fewer water samples from southern OCF and be an indicator of large scale landscape change upriver.

Permafrost degradation across OCF is also a major factor in landscape changes and inputs of terrestrial material into the surrounding hydrology. Gaining a better understanding of active layer thickness and its variability over seasonal and annual timescales is important in following Arctic landscape fluctuations. As well, studying the sediment bulk carbon concentrations at different depths in soils across OCF would identify areas of greater organic carbon. This would also lead to a better understanding of the influx of DOC through the hydrology of OCF and its influence on down-river basins. Grouping that with inorganic carbon concentrations in the sediments would form a more complete understanding of the source of weathering constituents and the balance between the export and sequestration of $CO_2$ across OCF. The addition of discharge data through the year would also enhance our ability to estimate the possible export of carbon to downriver basins.

This research provides a baseline understanding of spatial variability in landscape impacts on the hydrology in OCF. Coupling these results with landcover data would provide an indication towards the specific landcover influencing the water chemistry.

Landcover data would also be useful for tracking landscape changes such as lake drainages and coupling those changes directly with water chemistry and isotope signatures.

Finally, water isotope tracers, nutrients, ions, carbon concentrations and isotope signatures can be used to create a mixing model which could allow for expansion of this methodology across other lake-rich permafrost regions and provide a comparable result for inter-annual and seasonal data. Isotope signatures would include end member values for evaporated water (representing lake water infiltration), snowmelt, and rainwater to separate and identify source water. Water chemistry values can be used to interpret landcover impacts on the hydrology and identify spatial variability in landcover across OCF. This model would create a single number that would encompass the suite of water chemistry parameters and highlight likely factors that impact the hydrology and landscape changes over time.

## 4.4 References

Costard, F., Gautier, E., Brunstein, D., Hammadi, J., Fedorov, A., Yang, D., Dupeyrat, L., 2007. Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia. Geophys. Res. Lett. 34. doi:10.1029/2007GL030212

Jones, B.M., Grosse, G., Arp, C.D., Jones, M.C., Walter Anthony, K.M., Romanovsky, V.E., 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. J. Geophys. Res. 116. doi:10.1029/2011JG001666

Kokelj, S.V., Jorgenson, M.T., 2013. Advances in Thermokarst Research: Recent Advances in Research Investigating Thermokarst Processes. Permafr. Periglac. Process. 24, 108–119. doi:10.1002/ppp.1779

Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L., Coutts, R., 2009. Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada. Permafr. Periglac. Process. 20, 173–184. doi:10.1002/ppp.642

Lafrenière, M.J., Louiseize, N.L., Lamoureux, S.F., 2017. Active layer slope disturbances affect seasonality and composition of dissolved nitrogen export from High Arctic headwater catchments. Arct. Sci. 3, 429–450. doi:10.1139/as-2015-0009

Lamhonwah, D., Lafrenière, M.J., Lamoureux, S.F., Wolfe, B.B., 2017. Multi-year impacts of permafrost disturbance and thermal perturbation on High Arctic stream chemistry. Arct. Sci. 3, 254–276. doi:10.1139/as-2016-0024

Lantz, T.C., Kokelj, S.V., 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophys. Res. Lett. 35. doi:10.1029/2007GL032433

Lantz, T.C., Turner, K.W., 2015. Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. J. Geophys. Res. Biogeosciences 120, 513–524. doi:10.1002/2014JG002744

Riordan, B., Verbyla, D., McGuire, A.D., 2006. Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. J. Geophys. Res. Biogeosciences 111. doi:10.1029/2005JG000150

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., Olefeldt, D., Romanovsky, V.E., Schaefer, K., Turetsky, M.R., Treat, C.C., Vonk, J.E., 2015. Climate change and the permafrost carbon feedback. Nature 520, 171–179. doi:10.1038/nature14338

Smith, L.C., Sheng, Y., MacDonald, G.M., Hinzman, L.D., 2005. Disappearing Arctic Lakes. Science 308, 1429.

Stich, H.B., Brinker, A., 2005. Less is better: Uncorrected versus pheopigment-corrected photometric chlorophyll-a estimation. Arch. Fr Hydrobiol. 162, 111–120. doi:10.1127/0003-9136/2005/0162-0111

Strickland, J.D., Parsons, T.R., 1972. A practical handbook of seawater analysis.

Toniolo, H., Kodial, P., Hinzman, L.D., Yoshikawa, K., 2009. Spatio-temporal evolution of a thermokarst in Interior Alaska. Cold Reg. Sci. Technol. 56, 39–49. doi:10.1016/j.coldregions.2008.09.007

Turner, K.W., Edwards, T.W.D., Wolfe, B.B., 2014a. Characterising Runoff Generation Processes in a Lake-Rich Thermokarst Landscape (Old Crow Flats, Yukon, Canada) using $\delta^{18}O$, $\delta^{2}H$ and d-excess Measurements: Characterising Runoff with Water Isotope Tracers in Old Crow Flats, Yukon. Permafr. Periglac. Process. 25, 53–59. doi:10.1002/ppp.1802

Turner, K.W., Wolfe, B.B., Edwards, T.W.D., 2010. Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. J. Hydrol. 386, 103–117. doi:10.1016/j.jhydrol.2010.03.012

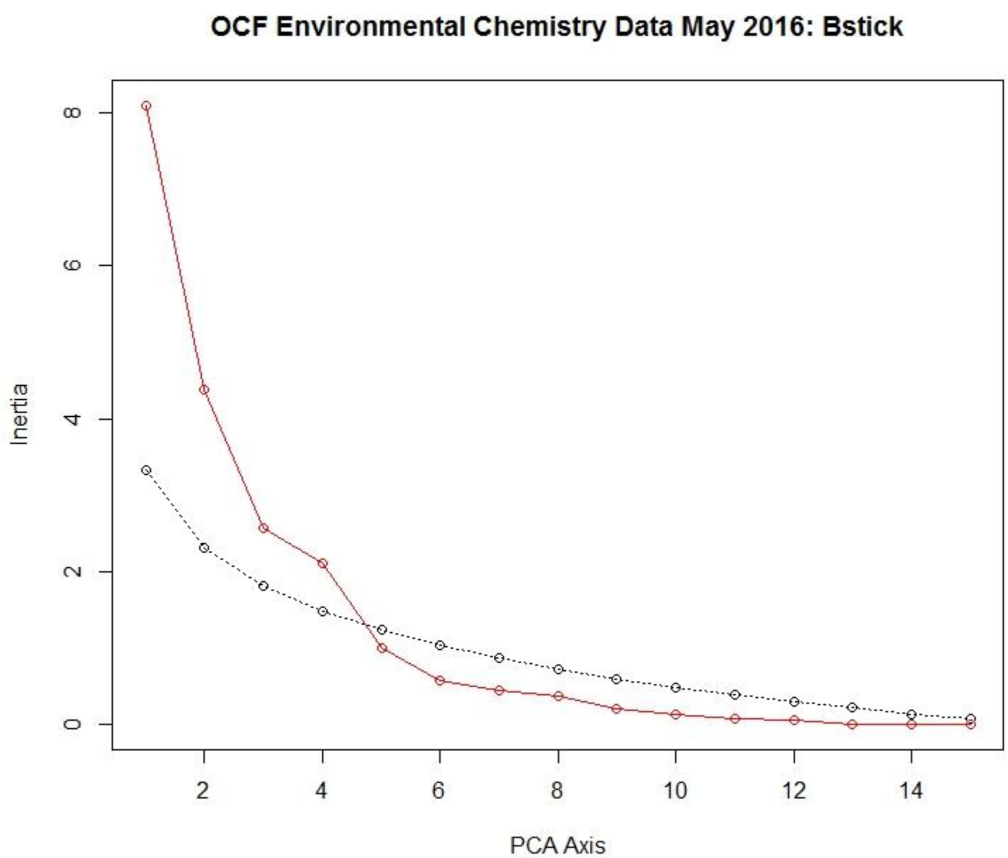
Turner, K.W., Wolfe, B.B., Edwards, T.W.D., Lantz, T.C., Hall, R.I., Larocque, G., 2014b. Controls on water balance of shallow thermokarst lakes and their relations with catchment characteristics: a multi-year, landscape-scale assessment based on water isotope tracers and remote sensing in Old Crow Flats, Yukon (Canada). Glob. Change Biol. 20, 1585–1603. doi:10.1111/gcb.12465

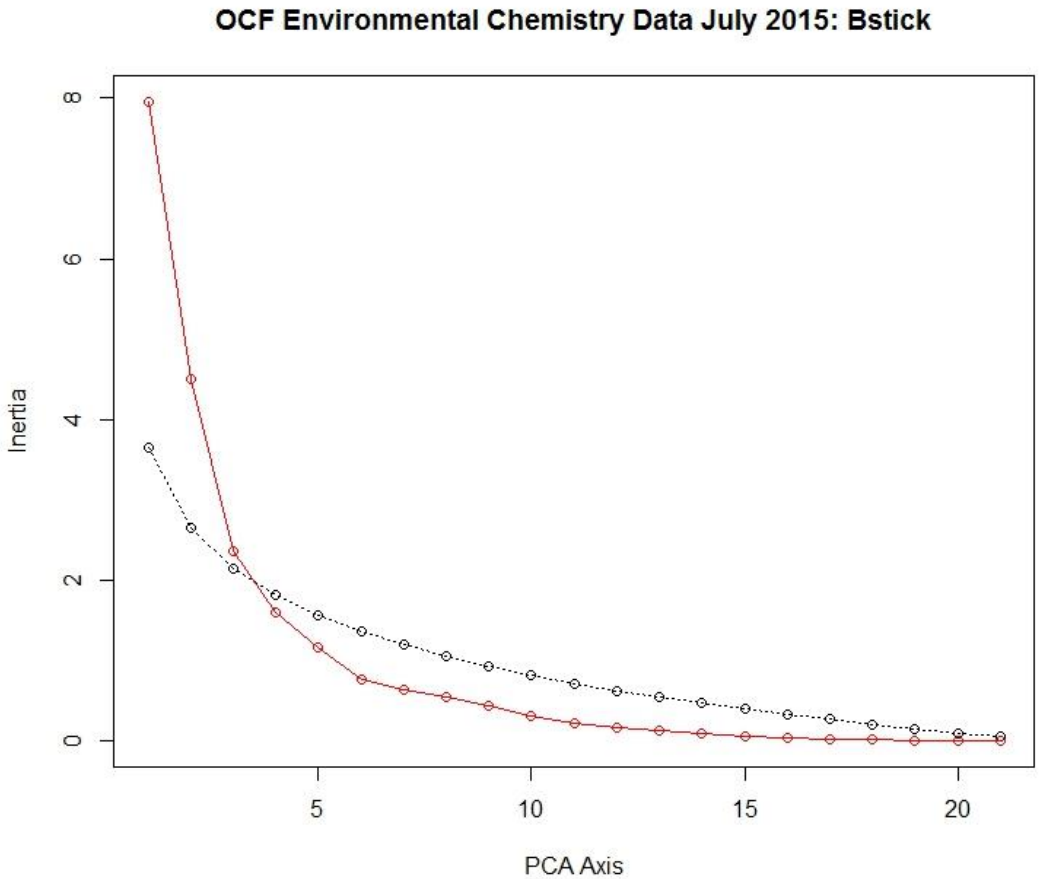
Appendix A

The broken stick (bâton brisé) distribution is a calculation of expected values as displayed by equation 1 from (Frontier, 1976):

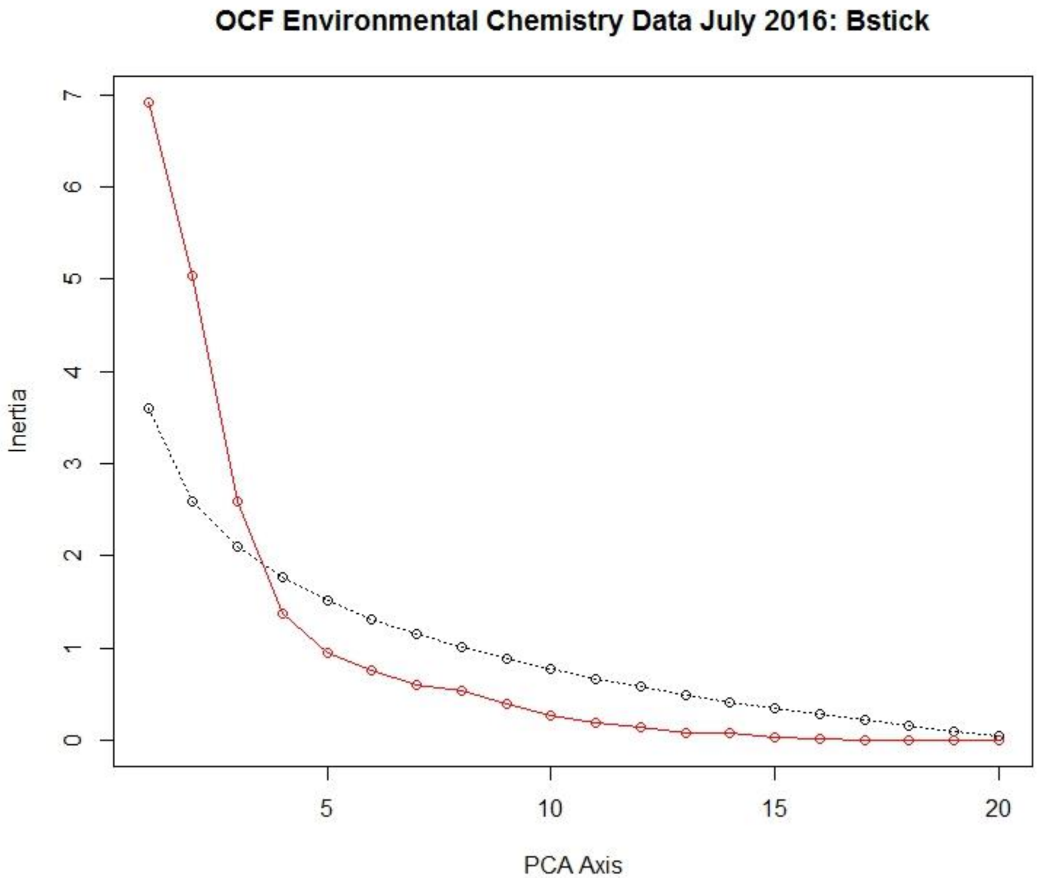
$$E(piece_j) = \frac{1}{p}\sum_{x=j}^{p}\frac{1}{x}$$

The expected values are based on a stick of unit length which can be broken at random into pieces (p) using a uniform random number generator (Legendre and Legendre, 1998). Principal components which fall above the broken stick distribution are considered statistically significant and are retained.




OCF Environmental Chemistry Data July 2015: Bstick
Inertia
0
2
4
6
8
5
10
15
20
PCA Axis

b


OCF Environmental Chemistry Data July 2016: Bstick
Inertia
PCA Axis
0
1
2
3
4
5
6
7
5
10
15
20